

A report requested by the Mars Exploration Program Analysis Group

Mars Astrobiology Explorer-Cacher (MAX-C): A Potential Rover Mission for 2018

Final Report of the Mars Mid-Range Rover Science Analysis Group (MRR-SAG)

October 14, 2009

Recommended bibliographic citation:

MEPAG MRR-SAG (2009) Mars Astrobiology Explorer-Cacher: A potential rover mission for 2018, Final report from the Mid-Range Rover Science Analysis Group (MRR-SAG), 94 pp., posted November 10, 2009, by the Mars Exploration Program Analysis Group (MEPAG) at <http://mepag.jpl.nasa.gov/reports/>.

Or:

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JPL Document Review Clearance CL#09-4589

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Acknowledgements:

We are grateful to these outside experts who assisted our team in answering questions:
Fernando Abilleira, F. Scott Anderson, Paul Backes, Don Banfield, Luther Beegle, Rohit Bhartia, Jordana Blacksberg, Diana Blaney, Karen Buxbaum, Shane Byrne, John Eiler, Sabrina Feldman, Lori Fenton, Kathryn Fishbaugh, Marc Fries, Matt Golombek, Bob Haberle, Samad Hayati, Michael Hecht, Arthur (Lonne) Lane, Lucia Marinangeli, Richard Mattingly, Tim Michaels, Denis Moura, Zacos Mouroulis, Mike Mumma, Scot Rafkin, Carol Raymond, Glenn Sellar, Christophe Sotin, Rob Sullivan, Tim Swindle, Marguerite Syvertson, Ken Tanaka, Peter Thomas, Lawrence A. Wade, Ben Weiss, Richard Zurek, and the MEPAG Goals Committee. Some of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. In the early parts of this study, the contributions of Hap McSween were important.

TABLE OF CONTENTS

1. 2-PAGE EXECUTIVE SUMMARY.....	4
2. INTRODUCTION.....	6
3. SCIENTIFIC PRIORITIES FOR A POSSIBLE LATE DECADE ROVER MISSION	8
4. DEVELOPMENT OF A SPECTRUM OF POSSIBLE MISSION CONCEPTS	11
5. EVALUATION, PRIORITIZATION OF CANDIDATE MISSION CONCEPTS	13
6. STRATEGY TO ACHIEVE PRIMARY <i>IN SITU</i> OBJECTIVES.....	17
7. RELATIONSHIP TO A POTENTIAL SAMPLE RETURN CAMPAIGN.....	25
8. CONSENSUS MISSION VISION	33
9. CONSIDERATIONS RELATED TO LANDING SITE SELECTION.....	35
10. SOME ENGINEERING CONSIDERATIONS RELATED TO THE CONSENSUS MISSION VISION	42
11. REFERENCES.....	47
12. APPENDIX A. MRR-SAG CHARTER AND PROCESS	61
13. APPENDIX B. MISSION CONCEPTS EVALUATED	64
14. APPENDIX C. POSSIBLE AUGMENTATION PACKAGES	85
15. APPENDIX D. SOME NOTES ABOUT POSSIBLE WAYS TO REDUCE THE MASS OF THE ROVER.....	90
16. APPENDIX E. PLANETARY PROTECTION CONSIDERATIONS FOR FUTURE MISSIONS THAT CACHE SAMPLES FOR POTENTIAL RETURN TO EARTH.....	92
17. APPENDIX F. ACRONYMS AND ABBREVIATIONS	93

1. 2-PAGE EXECUTIVE SUMMARY

This report documents the work of the Mid-Range Rover Science Advisory Group (MRR-SAG), which was assigned to formulate a concept for a potential rover mission that could be launched to Mars in 2018. Based on programmatic and engineering considerations as of April, 2009, our deliberations assumed that the potential mission would use the Mars Science Laboratory (MSL) sky-crane landing system, would include a single solar-powered rover, would have a targeting accuracy of ~ 7 km (semi-major axis landing ellipse), would have a mobility range of at least 10 km, and would have a lifetime on the martian surface of at least one Earth year. An additional key consideration, given recently declining budgets and cost growth issues with MSL, is that the proposed rover must have **lower cost and cost risk than those of MSL**—this is an essential consideration for Mars Exploration Program Analysis Group (MEPAG). The MRR-SAG was asked to formulate a mission concept that would address two general objectives: (1) **conduct high-priority *in situ* science** and (2) **make concrete steps towards the potential return of samples to Earth**. The proposed means of achieving these two goals while balancing the trade-offs between them are described here in detail. We propose the name Mars Astrobiology Explorer-Cacher (MAX-C) to reflect the dual purpose of this potential 2018 rover mission.

A key conclusion is that the capabilities needed to carry out compelling, breakthrough science at the martian surface are the same as those needed to select samples for potential sample return, and to document their context. This leads to a common rover concept with the following attributes:

- Mast- or body-mounted **instruments capable of establishing local geologic context** and identifying targets for close-up investigation. This could consist of an optical camera and an instrument to remotely determine mineralogy. Documentation of the field context of the landing site would include mapping outcrops and other accessible rocks, characterization of mineralogy and geochemistry, and interpretation of paleoenvironments.
- A tool to produce a **flat abraded surface** on rock samples.
- A set of arm-mounted instruments capable of **interrogating the abraded surfaces** by creating co-registered 2-D maps of visual texture, major element geochemistry, mineralogy, and organic geochemistry. This information would be used to understand the diversity of the samples at the landing site, to formulate hypotheses for the origin of that diversity, and to seek candidate signs of past life preserved in the geologic record. This information could also be used to select an outstanding set of rock core samples for potential return to Earth.
- A **rock core acquisition, encapsulation, and caching system** of the standards specified by MEPAG Next Decade Science Analysis Group (ND-SAG) (2008). This cache would be left in a position (either on the ground or on the rover) where it could be recovered by a future potential sample return mission.

We propose the following summary primary scientific objectives for the potential MAX-C mission:

At a site interpreted to represent high habitability potential, and with high preservation potential for physical and chemical biosignatures: evaluate paleoenvironmental conditions, characterize the potential for preservation of biotic or prebiotic signatures, and access multiple sequences of geological units in a search for evidence of past life and/or prebiotic chemistry. Samples necessary to achieve the proposed scientific objectives of the potential future sample return mission should be collected, documented, and packaged in a manner suitable for potential return to Earth.

The scientific value of the MAX-C mission would be significantly improved if it were possible to accommodate a **small secondary payload**. Highest priorities as judged by this team are basic atmospheric monitoring, an atmospheric-surface interactions instrument package, and a magnetometer.

The most important contribution of the proposed MAX-C mission to a potential sample return would be the assembly of a **returnable cache of rock core samples**. This cache would place the program on the pathway of a potential 3-element Mars **sample return campaign** (sampling rover mission, combined fetch rover plus Mars Ascent Vehicle (MAV) mission, and orbital retrieval mission). By preparing a cache, the proposed MAX-C rover would reduce the complexity, payload size, and landed operations time of a potential follow-on mission that would land the potential MAV, thus reducing the overall risk of that follow-on mission. This reduction in mass would facilitate bringing a potential sample return mission's landed mass within heritage (MSL) entry, descent, and landing capabilities. Even though caching would consume mission resources (e.g., money, mass, and surface operation time) that could alternatively be used for *in situ* scientific operations, the benefit to a potential sample return campaign would be compelling.

The proposed MAX-C rover would be **smaller than MSL, but larger than the Mars Exploration Rovers (MERs)**. This makes a reflight of the MSL Cruise/Entry, Descent, and Landing (EDL) system a prudent cost-effective choice to deliver the proposed MAX-C rover to the surface of Mars. Recent high level discussions between NASA and ESA have explored the idea of delivering the ESA ExoMars rover and the proposed NASA MAX-C rover to Mars together in 2018 on a single launch and MSL-type EDL system. This combined mission concept has been evaluated only briefly thus far. The implementation discussion in this report reflects a proposed NASA-only MAX-C mission, but the general capabilities would not be expected to change significantly for a joint mission architecture.

The proposed MAX-C mission would be launched in May of 2018 and arrive at Mars in January of 2019 at $L_s=325^\circ$ (northern mid-winter). Given the favorable atmospheric pressure at this season, performance of the MSL delivery system might allow altitudes up to +1 km, but altitude would trade off against the landed mass. There are also unfavorable effects on the atmosphere from an increased probability of dust storms, but the combined effects of these factors have not yet been fully evaluated. Latitude access for a solar powered rover with a minimum of a one Earth year primary mission lifetime is restricted to between 25°N and 15°S.

The mission concept would require **near-term technology development** in four key areas:

- Coring, encapsulation, and caching: Lightweight tools and mechanisms to obtain and handle cored samples.
- Scientific payload: Instruments capable of achieving the primary scientific objectives need to be matured, particularly for microscale mapping of mineralogy, organic compounds, and elemental composition.
- Planetary protection/contamination control: Methodologies for biocleaning, cataloging of biocontaminants, and transport modeling to ensure cached samples would be returnable.
- Rover navigation: Enhanced onboard image processing and navigation algorithms, in order to increase traverse rate.

As the next lander mission in the Mars Exploration Program, the proposed MAX-C mission would be a logical step in addressing MEPAG's goals, especially for astrobiology and geology objectives. It could be flown alone or with ExoMars and could be sent to a previously visited site or a new more-compelling site selected from orbital data, with sample return objectives included in the site selection criteria. It would be capable of yielding exciting *in situ* mission results in its own right, as well as making a significant feed-forward contribution to a potential sample return, likely becoming the first step in a potential sample return campaign.

2. INTRODUCTION

2.1. Background

As noted by MEPAG (2009), Mars has crustal and atmospheric characteristics that make it a priority exploration target for understanding the origins of life. The essential energy, water, and nutrient requirements to support and sustain life are currently present and the martian geologic record offers tantalizing clue of many ancient habitable environments (e.g., Knoll and Grotzinger, 2006; Squyres et al., 2008; Hecht et al., 2009). Recent data from orbiting and landed instrument have been studied by multiple teams of researchers, revealing a complexly dynamic planet with formation of rock units and structures influenced by impact events, crustal melting, tectonism, fluid/rock interactions, weathering, erosion, sedimentation, glaciation, and climate change (see for example, Christensen et al., 2003; Neukum et al., 2004; Howard et al., 2005; Tanaka et al., 2005; Bibring et al., 2006; Hahn et al., 2007; Arvidson et al., 2008, Frey, 2008; Smith et al., 2009; Squyres et al., 2009, Murchie et al., 2009). If life emerged and evolved on early Mars then it is possible, and indeed likely, that physical or chemical biosignatures are preserved in the exposed rock record. These extraordinary discoveries and inferences make a compelling case for a rover mission designed to explore for evidence of past martian life.

In the 2006 reports of the Mars Advance Planning Group (MAPG) (McCleese et al., 2006; Beaty et al., 2006), a mission concept was introduced that was generically referred to as “Mars mid-rover.” This was envisioned as a mission that could be considered for flight in 2016 or 2018, in follow-up to the MSL and ExoMars rovers. The mission concept involved twin “MER-derived rovers directed to different sites to explore the geologic diversity on Mars and, perhaps, search for organic material.” In February, 2008, the MEPAG MSS-SAG discussed the possible purpose and value of a single mid-range rover in more detail given our discoveries at Mars through 2007 and concluded that there could be three significant benefits:

- “Characterization of a new site follows up on discovery of diverse aqueous deposits
- Investigation of each type of deposit promises significant new insights into the history of water on Mars
- Provides additional context for proposed MSR samples”

The mid-range rover concept was also included in the planning work of the Mars Architecture Tiger Team (MATT) (Christensen et al., 2008, 2009). By the time of the MATT-3 report (Christensen et al., 2009), the potential mission was referred to with several different working names, including both Mid-Range Rover and Mars Prospector Rover, and the mission concept was generically envisioned as including a single “MER- or MSL-class rover with precision landing and sampling/caching capability”.

- At least MER-class rover would be deployed to new water-related geologic targets
- Precision landing (< 6-km diameter error ellipse) would enable access to new sites
- Would conduct independent science but with scientific and technical feed-forward to MSR
- As a precursor, this should demonstrate feed-forward capabilities for MSR and might open the possibility for payload trade-offs (e.g., caching and cache delivery) with the proposed MSR Lander

Although the strategic importance of a rover mission in about 2016-2018 to Mars exploration was recognized in each of the above planning documents, the specific purpose, rover size, and even number of rovers was deferred to a future science planning team. For example, none of the above reports penetrated the details of the possible scientific objectives (and the reasons why those objectives are important), how this mission would fit within an evolving programmatic context (most importantly, its relationship to MSL and a possible MSR mission), the investigation strategy, and the preliminary attributes of the rover that would be needed to carry out these objectives. MEPAG has therefore requested an analysis of scientific priorities and engineering implications for this mission concept.

2.2. MRR-SAG Charter

The MEPAG chartered a Mid-Range Rover Science Analysis Group (MRR-SAG) to analyze:

- possible scientific objectives of such a mission,
- the potential contribution of such a mission to the possible future return of samples from Mars, and
- any long-lead technologies that would enable or enhance the potential MRR mission and possible subsequent sample return.

The complete charter is provided in Section 12.1 (Appendix A) of this report.

The MRR-SAG was given the following guidelines for the analysis:

- The MRR mission should include a single solar powered rover, with a targeting accuracy of 3 km semi-major axis landing ellipse, a rover range of at least 5 km, a lifetime greater than one Earth year, and no requirement to visit a Planetary Protection Special region,
- The mission should have two purposes – to conduct high-priority *in situ* science and to prepare for potential sample return, and
- Given the forecasted budgetary environment, it is imperative to find mission options that would be lower cost and lower cost-risk than MSL.

After the charter was provided, during the MRR-SAG deliberations, engineers with expertise in Mars entry, descent, and landing (EDL) capabilities determined that the targeting accuracy and rover range guidelines needed adjustment. More realistic capabilities, which were used for the MRR mission concept analyzed in this report, are a semi-major axis landing ellipse of ~ 7 km and a rover range of at least 10 km.

The following specific tasks were assigned:

- (1) Evaluate the possible and probable discoveries from Mars Science Laboratory (MSL) and ExoMars that would feed forward to the 2018 (or 2020) opportunity.
- (2) Analyze the high-priority *in situ* science that could be accomplished based on Task 1, the MEPAG Goals Document (MEPAG, 2008), and recent NRC reports. Propose draft statements of the scientific objectives for this mission. Evaluate the kinds of instruments, kinds of landing sites, and nature of surface operations that would be needed to achieve the scientific objectives.
- (3) Determine the most important ways (scientific and technical) in which this mission could contribute to a potential sample return.
- (4) Analyze the trade-offs associated with simultaneously optimizing Tasks (2) and (3).
- (5) Analyze the incremental value to either *in situ* science or potential sample return feed-forward or both, which could be achieved with a modest increase in budget over the baseline assumptions specified above.

As a consequence of feedback from the Mars Architecture Review Team (MART) on a presentation of preliminary findings partway through the analysis, and in consultation with the MEPAG Chair and Mars Program administrators, the SAG responded to additional questions that clarify findings on the above tasks and more completely explore the engineering complexity of a sample cache.

The membership of the MRR-SAG is listed on page ii. Team members were selected by the MEPAG Executive Committee to represent the diversity in expertise within the Mars Program. They have considerable experience in Mars science, in previous and ongoing Mars spacecraft missions, and from membership on MEPAG and other NASA advisory groups. The 27-member team has six non-U.S. members, of whom four are involved in ExoMars. The team also included three JPL engineers. The

SAG also elicited assistance from about 30 other scientists and engineers (see page ii) in areas where additional expertise was needed.

Right before the MEPAG meeting (July 29-30, 2009), news stories reported the possibility that NASA and ESA might decide to fly a joint mission, sending the ExoMars rover and a NASA rover smaller than MSL on the same landing system in 2018. This new scenario would delay the launch of ExoMars from the 2016 launch opportunity to 2018. Because of the timing of this news, a detailed analysis of the option to fly an MRR rover with ExoMars was beyond the scope of the MRR-SAG. However, even if flown together, the two rovers would probably have different lifetimes and strategies, and would eventually end up traversing to different locations. To minimize risk and maximize scientific return, the concept of the MRR rover as proposed in this report would still be a sensible one, even if flown together with ExoMars. We leave the detailed analysis of this option to future study groups.

To provide a name that fit the mission concept better, the MRR-SAG changed the name of their concept from the generic Mid-Range Rover (MRR) to **Mars Astrobiology Explorer-Cacher (MAX-C)** toward the end of their deliberations in August 2009, and this updated name is used in the rest of this report.

3. SCIENTIFIC PRIORITIES FOR A POSSIBLE LATE DECADE ROVER MISSION

The Mars Exploration Program Analysis Group (MEPAG) actively maintains a prioritized, consensus-based list of four broad scientific objectives that could be achieved using the ongoing flight program (MEPAG, 2008):

- Determine whether life ever arose on Mars,
- Understand the processes and history of climate on Mars,
- Determine the evolution of the surface and interior of Mars, and
- Prepare for human exploration.

At present, the emphasis of the Mars Exploration Program is on the objective of determining whether life ever arose on the planet. Searching for signs of life on another planetary body requires a detailed understanding of the diversity of life as well as the environmental limits and evolutionary adaptations of life for different physical and chemical settings on Earth. Exploration for life on Mars requires a broad understanding of integrated planetary processes in order to identify those locations where habitable conditions are most likely to exist today or to have existed in the past and where conditions are or were favorable for preservation of the evidence of life if it ever existed. Any endeavor to search for signs of life therefore must also seek understanding of:

- The geological and geophysical evolution of Mars,
- The history of Mars' volatiles and climate,
- The nature of the surface and subsurface environments, now and in the past,
- The temporal and geographic distribution of liquid water, and
- The availability of other resources (e.g., energy) necessary for life.

Over most of the last decade, the Mars Exploration Program has pursued a strategy of “follow the water” (formally introduced in 2000; see documentation in MEPAG, 2008). While this strategy has been highly successful in the Mars missions of 1996-2007 (MPF, MGS, ODY, MER, MEX, MRO, and PHX), it is increasingly appreciated that assessing the full astrobiological potential of martian environments requires going beyond the identification of locations where liquid water was present (e.g., Knoll and Grotzinger, 2006; Hoehler, 2007). Thus, in order to seek signs of past or present life on Mars, it is necessary to characterize more comprehensively the macroscopic and microscopic fabric of sedimentary materials, identify organic molecules, reconstruct the history of mineral formation as an indicator of preservation potential and geochemical environments, and determine specific mineral compositions as indicators of

oxidized organic materials or coupled redox reactions characteristic of life. This type of information would be critical to select and cache relevant samples for addressing the life question in samples intended for study in sophisticated laboratories on Earth.

Two landed Mars missions are currently in development. Although neither has yet returned data, for the purpose of planning, we need to be cognizant of their objectives and possible results. NASA's Mars Science Laboratory (MSL) scheduled for launch in 2011 has the following objectives (Crisp et al., 2008):

- Assess the biological potential of at least one target environment,
- Characterize the geology and geochemistry of the landing region,
- Investigate planetary processes relevant to past habitability, and
- Characterize the broad spectrum of surface radiation

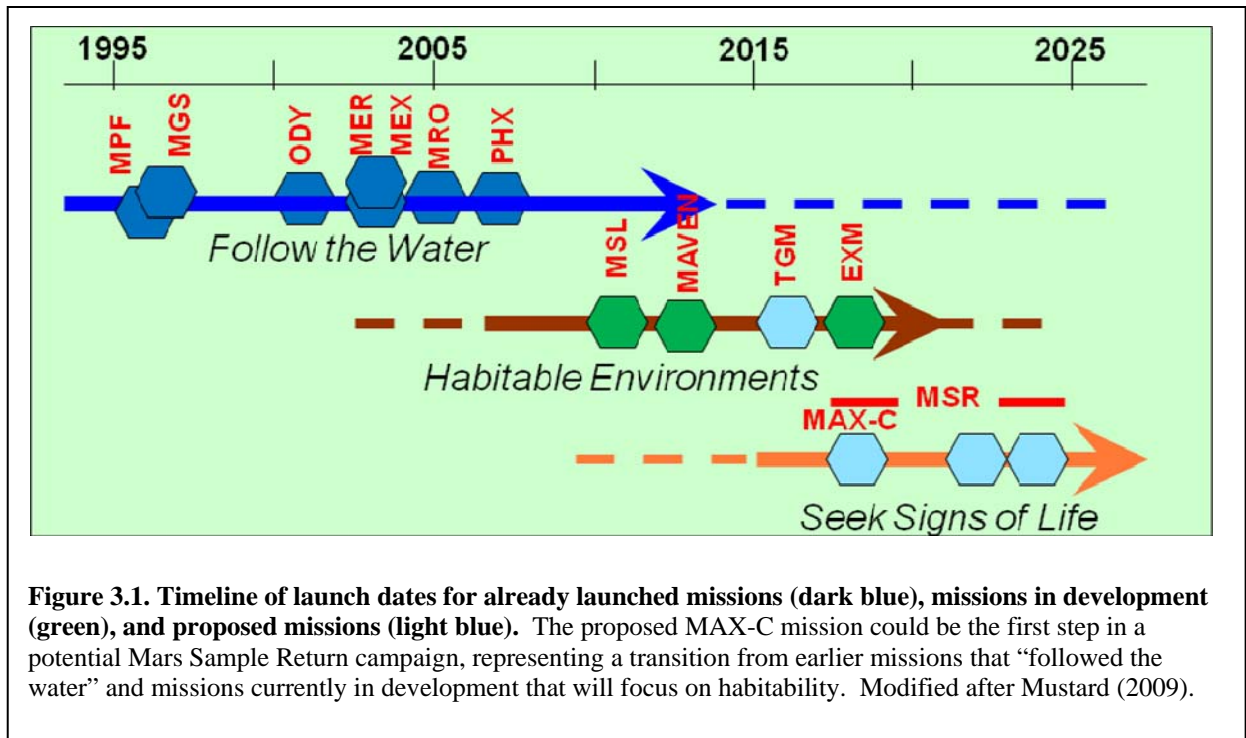
ExoMars which ESA plans to launch in 2018 has the following objectives (Vago et al., 2006):

- To search for signs of past and present life on Mars,
- To characterize the water/geochemical distribution as a function of depth in the shallow subsurface,
- To study the surface environment and identify hazards to potential future human missions, and
- To investigate the planet's subsurface and deep interior, to better understand the evolution and habitability of Mars.

The "Follow the Water" theme served Mars exploration well by connecting discipline goals in our investigations of Mars just as those processes (geological, geophysical, meteorological, chemical, and potentially biological) have been connected through Mars history. As the numerous missions to Mars have revealed the diversity of its environments and the complexity of its history, other themes have emerged which MEPAG has considered and which NASA, to some extent, has adopted:

- Introduced in 2000: **Follow the Water** [MGS, ODY, MER, MEX, MRO, PHX]
- Introduced in 2004: **Understand Mars as a System** [All missions]
- Introduced in 2005: **Seek Habitable Environments** [MSL, MSR]

As summarized by MEPAG (2009), the focus of potential missions should be to explore habitable environments of the past and present, including the "how, when and why" of environmental change. Although quantitatively assessing environmental habitability is the objective of MSL, the growing body of information about the diverse aqueous environments of Mars indicates that we are ready for more ambitious next steps. The NRC (2007) recently concluded, "The search for evidence of past or present life, as well as determination of the planetary context that creates habitable environments, is a compelling primary focus for NASA's Mars Exploration Program." These considerations have led MEPAG to adopt (at the July, 2009 MEPAG meeting) "**Seek the Signs of Life**" as its next broad strategy (MEPAG, 2009; Mustard, 2009). There is a drive to have the proposed MAX-C rover mission be first major mission designed to support this new strategy (see Figure 3.1).



Sample return from Mars has been advocated by numerous scientific advisory panels for over 30 years, most prominently beginning with the NRC’s (1978) strategy for the exploration of the inner solar system, and most recently by MEPAG’s ND-SAG (2008) panel. It remains the highest priority potential future mission in the Mars Exploration Program. Analysis of samples here on Earth has enormous advantages over *in situ* analyses. Instead of a small, predetermined set of analytic techniques applied to samples analyzed *in situ*, a return of samples would enable the analytical approach to be all-encompassing and flexible. State of the art analytical resources of the entire scientific community could be applied to the samples and the analytical emphasis could shift as the meaning of each result becomes better appreciated. Sample return has, however, been repeatedly deferred mainly for budgetary reasons.

The possible strategy of using rovers prior to MSR to collect and cache geological samples for possible subsequent return to Earth has been discussed as far back as at least the mid-1990s. The brief mention by Shirley and Haynes (1997) clearly shows that this was being discussed as a conceptual planning option at that time. MacPherson et al. (2002) and Steele et al. (2005) also briefly discussed sample caching, but particularly noted the potential difficulties of surface rendezvous. These reports were written in the context of MERs that were designed to last for only 90 sols and to travel 600 m (Crisp et al., 2003), so the challenges of physically recovering potential caches appeared quite daunting. The first detailed discussion of caching is presented by MacPherson et al. (2005). They point out some of the major advantages of caching, including reducing time on the surface for the potential MAV, improving sample documentation by a prior mission that would have more time, and the engineering advantages of sending the potential MSR lander into known terrain. In the MAPG programmatic planning report (Beatty et al., 2006), sample caching was recognized as a strategy to increase the scientific value of a potential future sample return. It would improve the quality of the sample collection returned by a potential MSR by allowing more information to go into sample selection decisions. This was followed up by the NRC (2007), who recommended “sample caching on all surface missions that follow the Mars Science Laboratory, in a way that would prepare for a relatively early return of samples to Earth.” In mid-2007, NASA directed that a very simple cache (McKay et al., 2007; Karcz et al., 2008b; design documented by Karcz et al., 2008a) be added to the MSL rover. At the time, MSL was very advanced in its design

process, which resulted in a number of significant constraints. Although they endorsed the potential value of sample caching, Steele et al. (2008) and MEPAG ND-SAG (2008) raised serious concerns regarding sample quality for this specific implementation. In November 2008, given the advanced state of MSL's design, it was decided that this cache could not be added without significant consequences in other areas, and the cache was descope from MSL. Finally, a number of the MSR-related white papers submitted to the 2009 Planetary Decadal survey discuss the potential strategic importance of MSR-related sample caching, including Borg et al. (2009), Farmer et al. (2009), Hand et al. (2009), Hayati et al. (2009), Jakosky et al. (2009), MEPAG (2009), Neal et al. (2009), and Steele et al. (2009).

4. DEVELOPMENT OF A SPECTRUM OF POSSIBLE MISSION CONCEPTS

To assess whether the prospective rover mission could meet the scientific goals of the Mars program within the constraints provided, the panel undertook the exercise of defining and evaluating potential mission scenarios to achieve current program priorities and to determine the rover capabilities that would be required to accomplish the mission objectives. Building on the long history of scientific exploration on Mars, it is possible to frame a diverse array of highly informed and specific scientific objectives that lay out a path for far-reaching insights to the planet. Many of the key scientific objectives could be addressed with an *in situ* rover mission, and the MRR-SAG committee compiled a list of 28 such objectives that they felt could be addressed by a potential MAX-C mission. Some of the objectives pertain to application of specific types of measurements (or approaches to measurements) that would be valuable for addressing several different scientific questions, whereas others describe the important scientific objectives themselves, without specification of measurements or approaches. Thus, there are many conceptual overlaps and interrelationships within the list. Six broad scientific themes emerged from the list:

- The search for extant life on Mars
- The search for evidence of past life on Mars
- Understanding martian climate history
- Determination of the ages of geologic terrains on Mars
- Understanding surface-atmosphere interactions on Mars
- Understanding martian interior processes

The possible scientific objectives and scientific themes could be organized into eight mission concepts (Table 4.1). These mission concepts encompass one or more of the scientific themes listed above. The MEPAG Goals Committee reviewed these mission concepts for completeness and clarity. They pointed out some ways of consolidating the list to make it more useful, which helped to focus in on the definition of the various concepts, but they did not contribute any additional new mission concepts. This helped give us confidence that we had sufficiently covered the full spectrum of high-priority options. SAG members self-selected into eight subgroups (one for each mission concept) that worked to identify fundamental scientific questions, essential information needed, landing site considerations, and mission implementation. These eight mission concepts are described more fully in Appendix A.

The MRR-SAG also identified several possible augmentations to these missions, which might be accommodated if sufficient funding were available. These augmentations (landed atmospheric science, paleomagnetic measurements, and radiometric dating) are described in Section 5.3 and in more depth in Section 14 (Appendix C). Note that two of the mission concepts (#3 Radiometric Age Determination and #6 Deep Drilling) could also be considered as augmentations to other mission concepts.

FINDING: Several rover-based mission concepts with compelling scientific objectives have been identified for the 2018 opportunity.

Table 4.1. Mission concepts and proposed primary objectives. Note: numbers are the SAG’s reference numbers only, and do not indicate rankings.

Ref #	Mission Concept	Primary Scientific Objectives
1	Mission to core and analyze subsurface ice at mid-latitudes	Scientific objectives would be to characterize periglacial sites and the habitability and <i>in situ</i> resource utilization potential of shallow ice deposits; this concept is similar in some respects to some Phoenix objectives, but examines mid-latitude deposits.
2	Mission to study a stratigraphic sequence at or near the Noachian-Hesperian boundary	Scientific objectives would be to understand how the environment changed during this interval, to define its absolute age, and explore the implications of these environmental changes for habitability, preservation of biosignatures, and life.
3	Mission to provide radiometric age determinations of surface materials	Scientific objectives would be to determine the absolute ages of a stratigraphic sequence important to astrobiology in support of another overall mission concept, or to provide calibration for crater retention.
4	Mission to an Early Noachian terrain	Scientific objectives would address questions about the planet’s earliest history, possible transition from prebiotic to biologic chemistry and primitive cells, and biologic evolution in relation to changes in the planet’s magnetic field, atmosphere, and impact rate.
5	Mission to an astrobiology-relevant site that is distinct from others previously visited	Scientific goals would include searching for any evidence of life and determining if that evidence could be collected; this concept is not as specific as others.
6	Mission that incorporates deep (~2 m) drilling	Scientific objectives would be to understand surface oxidation and its effect on organic carbon and life; this concept overlaps a goal of ExoMars.
7	Mission to a modern methane seep	Scientific objectives would be to analyze methane and associated reduced gases emitted from the subsurface and assess their possible connection to life.
8	Mission to traverse and analyze polar layered deposits	Scientific objectives would be to assess global climate change and secular evolution of water.

5. EVALUATION, PRIORITIZATION OF CANDIDATE MISSION CONCEPTS

5.1. Concept Prioritization

The SAG prioritized the candidate mission concepts using the following criteria: scientific value, scientific risk, and breakthrough potential. The priority rankings are given in Table 5.1. Three concepts (reference #s 4, 2, and 5) clearly ranked higher than the rest. Several mission concepts were determined to be not currently viable, for various reasons. A mission to obtain absolute radiometric ages for surface

Table 5.1. Scientific prioritization of the eight mission concepts. MRR-SAG members scored each concept from 1 (low value, high risk, low breakthrough potential) to 3 (high value, low risk, high breakthrough potential). Average scores of the MRR-SAG votes are listed below. Green boxes highlight the averaged scores > 2.5.

Ref. #	Mission Concept	PRIORITY			
		Science value	Science Risk	Breakthrough Potential	OVERALL
4	Astrobiology Mission to Early Noachian Mars	2.7	2.3	2.6	2.5
2	Stratigraphic Sequence near Noachian-Hesperian Boundary	2.6	2.2	2.5	2.4
5	Astrobiology: New Terrain	2.5	2.1	2.4	2.3
7	Detection of Methane Emission from the Mars Subsurface	2.3	1.2	2.5	2.1
3	Radiometric Dating	2.3	1.5	2.1	1.9
6	'Deep' Drilling	1.9	1.6	1.9	1.8
8	Polar Layered Deposits Traverse	1.8	1.7	1.7	1.7
1	Mid-Latitude Shallow Ice	1.7	1.9	1.7	1.5

materials (Concept #3) was considered to offer potential future promise, but technologies allowing age determinations *in situ* appear to not yet be mature or cost effective (e.g., Conrad et al., 2009). A mission to investigate methane seeps (Concept #7) had strong astrobiological interest, but the SAG did not see a clear path that would provide sufficient information on the spatial distribution of such seeps to allow targeting for the 2018 launch opportunity, even with a potential Trace Gas Mapper in 2016 (TGM; Smith et al., 2009a). This could be revisited later if TGM is selected, and after its capabilities have been defined. A potential mission to polar layered deposits (Concept #8) was not considered viable because the SAG was informed that it appears that there are no reasonably achievable trajectories to high latitude sites in the 2018 launch opportunity.

Moreover, a rover mission trying to last a year would have a severe power challenge at such high latitude. In addition to the rankings, members of the team were invited to add comments, explaining the reasons behind their rankings. These comments were compiled by concept, and within each concept organized into positive and negative remarks. A summary of the more notable points that were raised is given in Section 13.9 (Appendix B).

The MRR-SAG team had a mixture of scientific expertise that could be broadly grouped into three categories: geologists, astrobiologists, and atmospheric scientists + geophysicists. Because perspective on relative priority for concepts as diverse as these can be quite dependent on discipline balance, we show in Table 5.2 the relative priorities of the eight mission concepts as judged by these three discipline groups. Most importantly, Concepts #2 and #4 were rated the top two priorities by each of the three discipline groups, and Concept #5 was in third place for two of the groups, and closely following in fourth place for the other. The differences between these groups were that the atmospheric scientists saw higher value in Concept #1 (relating to mid-latitude ice), the astrobiologists saw higher value in Concept #7 (methane), and the geologists saw higher value in Concept #3 (age dating). However, the convergence of all sectors

of the team on Concepts #2, #4, and #5 is an important foundation for formulating a consensus mission concept.

5.2. Integration into a Single Mission Concept

Table 5.2. Top four mission concepts (indicated by reference numbers) in overall science priority, by MRR-SAG member primary discipline.

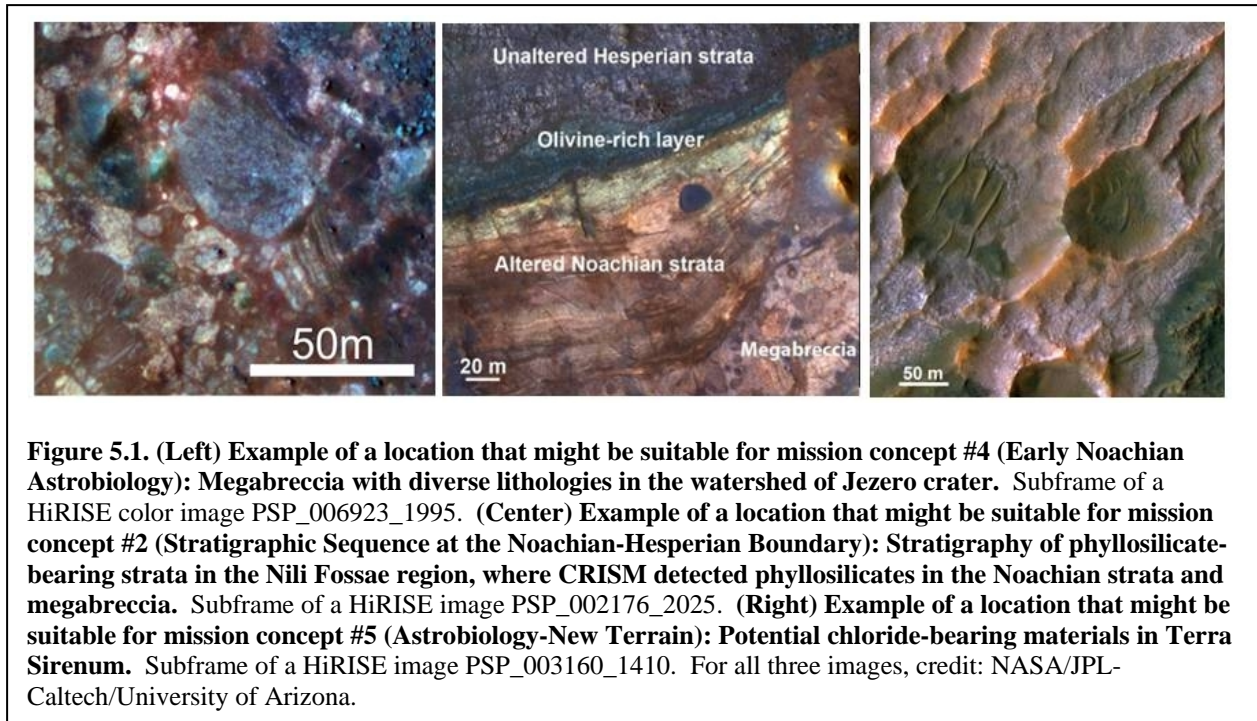
Overall Science Priority	Geologists (12 voting)	Astrobiologists (8 voting)	Atmospheric Scientists and Geophysicists (3 voting)
1	#4	#4	#2
2	#2	#2	#4
3	#3	#5	#5
4	#5	#7	#1

It is increasingly appreciated that assessing the full astrobiological potential of martian environments requires going beyond the identification of locations where liquid water is or was present (e.g., Knoll and Grotzinger, 2006). Thus, in order to seek signs of past or present life on Mars, basic requirements include more comprehensive characterization of the macroscopic and microscopic fabric of sedimentary materials, detection of organic molecules, reconstruction of the history of mineral formation as an indicator of preservation potential and geochemical environments, and determination of specific mineral compositions as indicators of oxidized organic materials or coupled redox reactions characteristic of life. This essential science lies at the heart of each of the top three candidate mission concepts, #2, #4, and #5. Example landing sites for these concepts are shown in Figure 5.1.

This leads us to conclude that a single rover with the same general capabilities could be used to explore a wide range of landing sites of relevance to all three of the candidate missions. Each of these three candidate mission concepts relates to astrobiology, they all entail understanding paleoenvironmental conditions, understanding preservation potential would be important for all of them, and they all are

of interest for assessing possible evidence of past life and/or prebiotic chemistry. A single general mission implementation would allow the Mars Exploration Program to respond to discoveries over the next several years in any of the above areas with the distinction between these scenarios resolved in a landing site competition.

MAJOR FINDING: A single rover with the same general capabilities and high-level scientific objectives could explore one of a wide range of landing sites relevant to the top three mission concepts. The differences between the concepts primarily relate to where the rover would be sent, rather than how it would be designed.



It is possible to frame a single statement of scientific objective (see below) that encompasses all three of these mission concepts. First, since one of the Mars Exploration Program’s current strategies is to evaluate differences in habitability potential as a function of both space and time, it is presumed that sites with comparatively high potential will have been identified as input to both mission planning and site selection. This is a crucial prioritization strategy that would allow the proposed MAX-C rover to be inserted into an environment with high scientific potential. Second, each of the high-priority mission concepts relates to ancient environments on Mars, rather than modern environments. Thus, the scientific objectives relate to the kinds of things one would want to do in such an environment, which include evaluating paleoenvironmental conditions, characterizing the potential for the preservation of biotic or prebiotic signatures, and accessing multiple sequences of geological units in a search for possible evidence of ancient life and/or prebiotic chemistry.

PROPOSED PRIMARY *IN SITU* SCIENTIFIC OBJECTIVES:

At a site interpreted to represent high habitability potential, and with high preservation potential for physical and chemical biosignatures:

- evaluate paleoenvironmental conditions,
- characterize the potential for the preservation of biotic or prebiotic signatures, and
- access multiple sequences of geological units in a search for possible evidence of ancient life and/or prebiotic chemistry

5.3. The Possibility of One or More Secondary Scientific Objectives

At this stage of planning, it is not clear what the final resource constraints on a possible next decade rover mission would be. For this reason, it is important to consider the possibility of secondary scientific objectives, for which it may ultimately be possible to fit necessary instruments within the mission’s resource limitations. A number of ideas were raised during the course of the team’s deliberations. On the basis of its collective sense of current scientific priorities and engineering/financial feasibility, the MRR-

SAG recognized two broad classes of investigation that appear to be particularly good candidates for the potential MAX-C mission, relating to landed atmospheric science and to paleomagnetic studies. In both cases, additional expertise was solicited to document the possible scientific objectives and possible implementation strategies—these amplified analyses are presented in Appendix C.

Landed atmospheric science. An important scientific objective related to landed atmospheric science would be to determine the relationships governing surface/atmosphere interaction through exchange of volatiles (including trace gases), sediment transport, and small-scale atmospheric flows, each of which is necessary to characterize Mars' present climate. Measurement of wind velocities, surface and air temperatures, relative humidity, dust emission (either through saltation impact or otherwise), air pressure, and trace gas fluxes are all necessary to determine the relationships controlling surface/atmosphere interactions. To properly characterize the exchange of momentum, heat, volatiles, and sediment between the surface and atmosphere, it would be necessary to have a dedicated suite of instruments that functions for extended periods of time and obtains precise measurements of high frequency so that subsecond, hourly, diurnal, seasonal, and interannual variations are resolved and monitored (Rafkin et al., 2009). With the current lack of martian observations, empirical relations acquired on Earth are typically applied to estimate fluxes between the martian surface and atmosphere, with unknown errors. Thus these data would be essential for understanding the current climatic state of Mars, determining potential sources of trace gases that might lead to the discovery of life, and constraining atmospheric models that are needed to ensure safe landing conditions for potential future spacecraft.

Within Section 14.1 (Appendix C) of this report, draft priorities within a multiple set of possible landed atmospheric scientific investigations are described, which could determine the relationships governing surface/atmosphere interaction through exchange of volatiles (including trace gases), sediment transport, and small-scale atmospheric flows. Of everything in the list, the most important is judged to be measurement of the atmospheric pressure, which is the 'heartbeat' of the atmospheric system (Rafkin et al., 2009) and would provide a measure of the total atmospheric mass, which is related to formation and sublimation of the polar ice caps (Titus et al., 2009).

Paleomagnetic studies. Objectives for paleomagnetic investigations are described in detail in Section 14.2 (Appendix C) and are also advocated in the Decadal Survey white paper by Lillis et al. (2009). Mars presently does not have a core dynamo magnetic field, but the discoveries of intense magnetic anomalies in the ancient southern cratered terrane by the Mars Global Surveyor mission (Acuna et al., 1998) and remanent magnetization in martian meteorite ALH 84001 (Kirschvink et al., 1997; Weiss et al., 2002) provide strong evidence for a martian dynamo active during the Noachian epoch. The time of origin and decay of this global field is poorly constrained but has critical implications for planetary thermal evolution (Stevenson, 2001), the possibility of an early giant impact (Roberts et al., 2009), the possibility of early plate tectonics (Nimmo and Stevenson, 2000), and the evolution of the martian atmosphere and climate (Jakosky and Phillips, 2001). Paleomagnetic studies yield two pieces of information: the intensity and the direction of ancient fields. Because the original stratigraphic orientations of martian meteorites are unknown, all Mars paleomagnetic studies to date have only been able to measure the paleointensity of the martian field (Weiss et al., 2008). *In situ paleomagnetic studies from a Mars rover would provide unprecedented geologic context and the first paleodirectional information on martian fields.* The data could be used to address at least four very important scientific questions:

- (1) When was the martian magnetic field present and when did it disappear? Did the death of the martian dynamo lead to atmospheric loss and climate change?
- (2) Did ancient magnetic fields definitely arise from a core dynamo?
- (3) How did the martian paleofield vary in time? Did it experience reversals and secular variation and if so what were their frequencies?
- (4) Did Mars experience plate tectonics and/or true polar wander?

Unlike landed atmospheric science packages (which have flown on missions including Viking and Pathfinder and also will be on the upcoming MSL mission), a paleomagnetism package has never been flown on any Martian lander.

Other possible secondary objectives considered included a geochronology experiment, a seismic investigation, and scientific objectives related to drill acquisition of subsurface samples. The judgment of the SAG was that although there are very strong scientific reasons for these investigations, they are of a character that would be more appropriate as the primary objective of a separate mission, not as a secondary objective squeezed into a mission that has an alternate primary purpose. If the resource parameters of the mission change significantly in the future, these possibilities should certainly be reconsidered.

Balancing all of the above possibilities with the realities of limitations on mass and money, the SAG concludes that at least one secondary payload should be accommodated, and that the single highest priority is an atmospheric pressure sensor.

FINDING: Inclusion of at least one secondary scientific objective would substantially enhance the scientific return of the proposed mission. The single highest priority would be to monitor the atmospheric pressure as a function of time at the martian surface.

6. STRATEGY TO ACHIEVE PRIMARY *IN SITU* OBJECTIVES

If rocks and outcrops are limited in extent within the landing ellipse (which may be a necessary condition to ensure safe landing), the important process of quickly constraining geologic setting, selecting sample locations, and providing context for samples might be challenging. Indeed, the MER experience shows that considerable time would be spent locating outcrops and evaluating them upon arrival. These considerations lead to the following finding:

FINDING: The proposed MAX-C mission must have the capability to define geologic setting and remotely measure mineralogy in order to identify targets for detailed interrogation by the arm-mounted tools from a population of candidates and place them in stratigraphic context.

In addition, interpretation of the geologic setting and placement of observations in stratigraphic context could be significantly enhanced by subsurface sensing, such as ground-penetrating radar or seismic profiling (although the latter is unlikely to be feasible). The potential MAX-C traverse capability would affect the specific requirements for remote sensing (resolution, downlink volume). Orbital data would be very useful for strategic traverse planning, but not sufficient for tactical planning.

Implementation of the proposed MAX-C mission objectives would require interpretation of the origin and subsequent modification of rocks with as-yet unknown mineral composition, macroscale structure, and degree of heterogeneity. Given these unknowns, it is challenging to identify the specific set of measurements that would be required in the future by such a rover mission. However, relevant experience from study of ancient terrestrial strata, martian meteorites, and from MER indicates that the proposed rover's interpretive capability should include:

- Mineralogical remote sensing at ~1 mrad/pixel or better, SNR > 100
- Geomorphological context (optical) imaging at ~0.3 mrad/pixel or better
- Abrasion of ~3 cm diameter areas on rocks
- Measurements of the abraded rock surfaces:

- Optical texture at $\sim 30 \mu\text{m}/\text{pixel}$ resolution or better, $\text{SNR} > 100$
- Mineralogical 2-D mapping with $\sim 0.3 \text{ mm}$ spatial resolution, $\text{SNR} > 100$
- Organic detector 2-D mapping with $\sim 0.1 \text{ mm}$ spatial sampling
- Elemental chemistry 2-D mapping with $\sim 0.1 \text{ mm}$ spatial resolution (if not possible to accommodate, then bulk chemical composition measured on a few-cm diameter spot)

For three primary reasons, we propose that the measurement strategy focus on interrogation of abraded surfaces: (1) We know from the results of MER that a variety of microscopic textures are present on Mars (see Figure 6.1), (2) We know that surface analysis techniques have significantly lower cost and risk in comparison to acquiring rock chips or powders (comparative experience from MER and MSL), and (3) A number of suitable instruments are either already developed or are under development in each of these four areas identified (see Section 6.1). This class of instruments makes use of a relatively smooth, abraded rock surface, such as is produced by the Rock Abrasion Tool (RAT) grinder on MER (Gorevan et al., 2003). Note that this strategy and the mission objectives would require access to outcrops, a consideration that has implications for the landing site attributes.

FINDING . Outcrop access is fundamental to the MRR mission concept. This has implications for landing site selection.

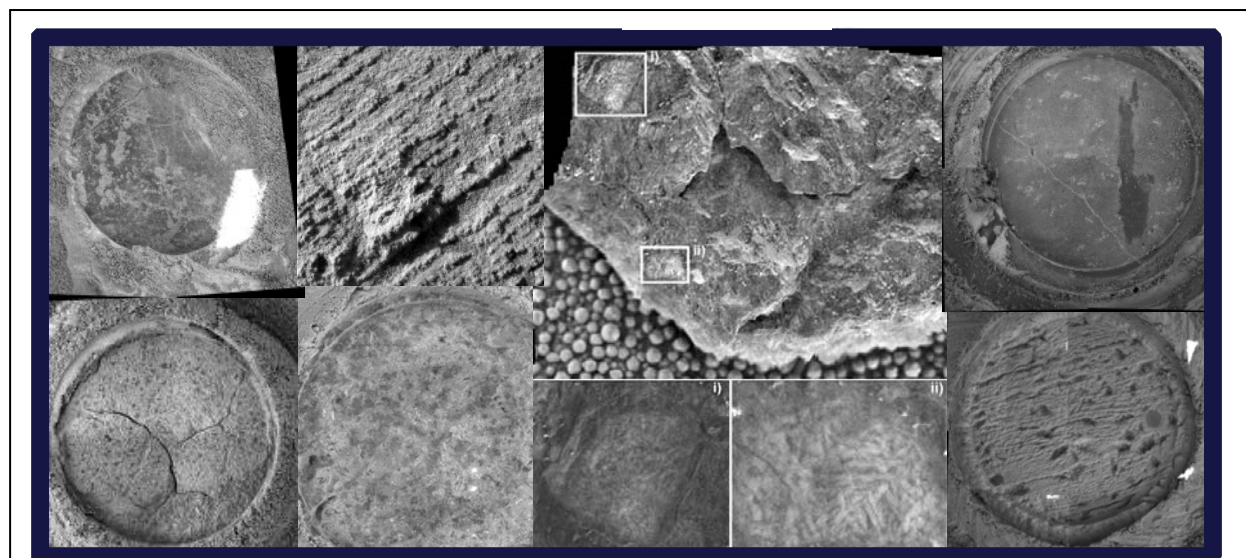


Figure 6.1. MER close-up visual examination has revealed interesting textures on relatively smooth rock surfaces of martian rocks, as shown in these example images. Credit: NASA/JPL-Caltech/USGS. Detailed results from the MER Microscopic Imager investigations are described in Herkenhoff et al. (2004, 2006, 2008). Micro-mapping could be used to study origins of minerals, depositional / formation sequences, presence and duration of liquid water, and the presence and nature of any organic deposits or biominerals.

For measurements of mineralogy and chemistry, instruments used to directly interrogate smoothed rock surfaces typically cannot match the analytical accuracy and precision attained by instruments that ingest samples. However, the data quality would be sufficient to meet key scientific objectives and the ability of such instruments to characterize intact outcrops would offer substantial advantages. Although in the past we have used instruments that average the analytic data over an area at least centimeters in size (e.g., Christensen et al., 2004; Clark et al., 2005; McLennan et al., 2005; Squyres and Knoll, 2005; Arvidson et al., 2006; Morris et al., 2006a, 2006b, 2008; Gellert et al., 2006; Glotch et al., 2006; Squyres et al., 2006); with newer instrumentation, spatial resolution down to scales of tens of micrometers is readily achievable

(see Section 6.1). Some instruments can produce data in a 2-D scanning mode, which would be exceptionally powerful. If observations of texture, mineral identification, major element content, and organic materials are spatially co-registered, they can interact synergistically to strengthen the ultimate interpretations. This 2-D micro-mapping approach is judged to have particularly high value for evaluating potential signs of ancient microbial life, key aspects of which are likely to be manifested at relatively small scale. We conclude that the 2-D micro-mapping investigation approach is an excellent complement to the data anticipated from MSL, which will have higher analytical precision but lower spatial resolution.

In Section 15 (Appendix D), a more detailed description of the proposed “science floor” replaces 2-D elemental mapping with bulk elemental analysis on a 1.5 to 2.5 cm diameter spot, relaxes the recommended required resolution of the mineralogical remote sensing and visible imaging, and relaxes the recommended required spatial resolution of *in situ* mineralogical mapping and organic compound measurements.

The panel concluded that recommendation of specific instruments to accomplish the recommended required measurements should be left to a future Science Definition Team, but recognized the need for a straw-man payload to support engineering trade studies and mission planning. We have carefully evaluated the available means of collecting these kinds of data without acquisition of rock chips or powders and have learned that a number of suitable instruments are either already developed or are under development (at least Technology Readiness Level-3) in each of these four areas identified. This class of instruments makes use of a relatively smooth, abraded rock surface, such as is produced by the Rock Abrasion Tool (RAT) on MER. We expect there to be some dependency of the accuracy and precision of measurement results on the physical character of the abraded surface. Some kinds of measurements of surfaces are affected by surface roughness, flatness, etc. Setting specific requirements in this area would need further study by a successor team.

6.1. Some Classes of Instruments Relevant to Primary *in situ* Objectives

The MRR-SAG arranged for a survey of the status and capabilities of various remote sensing and *in situ* instruments that could meet the proposed MAX-C objectives (credit to Dr. Sabrina Feldman, JPL). We found that there are a number of potentially important instruments that could meet the recommended measurement requirements of the proposed mission that currently have a Technology Readiness Level of at least TRL-3, although only a fraction are as advanced as TRL-6 (the state of readiness needed by the time of mission Preliminary Design Review). Continuing development of these instruments would be very important in supporting a good instrument competition in response to an Announcement of Opportunity for the proposed MAX-C mission.

FINDING: There are a number of potentially useful instruments that could meet the measurement requirements of the proposed mission that currently have a Technology Readiness Level (TRL) of at least TRL-3.

Some examples of these instruments that could be flown on the proposed MAX-C mission are described below. The purpose is not to advocate that these particular instruments should be a part of the proposed mission. Rather, these descriptions could be used by scientists to consider the full scientific potential of this sort of mission, and by engineers to check the feasibility of accommodating an instrument suite that could meet the recommended measurement objectives formulated in this report.

6.1.1. Multispectral Microscopic Imager (Robotic Arm-Mounted)

Microimaging capability – in the form of a geologist’s hand lens – has long been an essential tool for terrestrial field geology. Imagery at the hand-lens scale (several cm field-of-view resolved to several tens of microns) provided by the Microscopic Imagers on the Mars Exploration Rovers (MERs) and the Robotic Arm Camera (RAC; Keller et al., 2008) on the Phoenix lander have proven so vital to the success of these missions and to the Mars Exploration Program (Herkenhoff et al., 2004, 2006, 2008) that a microimager is one of the two instruments now recognized as essential for Mars surface missions (MEPAG ND-SAG 2008). The microtextures of rocks and soils, defined as the microspatial interrelationships between constituent mineral grains, pore spaces, and secondary (authigenic) phases (e.g., cements) of minerals, provide essential data for inferring both primary formational processes and secondary (postformational) diagenetic processes. Such observations are fundamental for properly identifying rocks, interpreting the paleoenvironmental conditions they represent, and assessing the potential for past or present habitability. Multispectral, visible-to-near-infrared microimages could provide context information for evaluating the spatial (and implied temporal) relationships between constituent mineral phases characterized by other mineralogical methods that lack context information. Microimaging could also provide highly desirable contextual information for guiding the subsampling of rocks for potential caching and/or additional analyses with other *in situ* instruments. Figure 6.2 shows 3-band-color-composite images, both natural-color and false-color, composed of bands selected and extracted from a 21-band visible/near-infrared image set acquired by the Multispectral Microscopic Imager (Sellar et al., 2007; Nuñez et al., 2009a, 2009b).

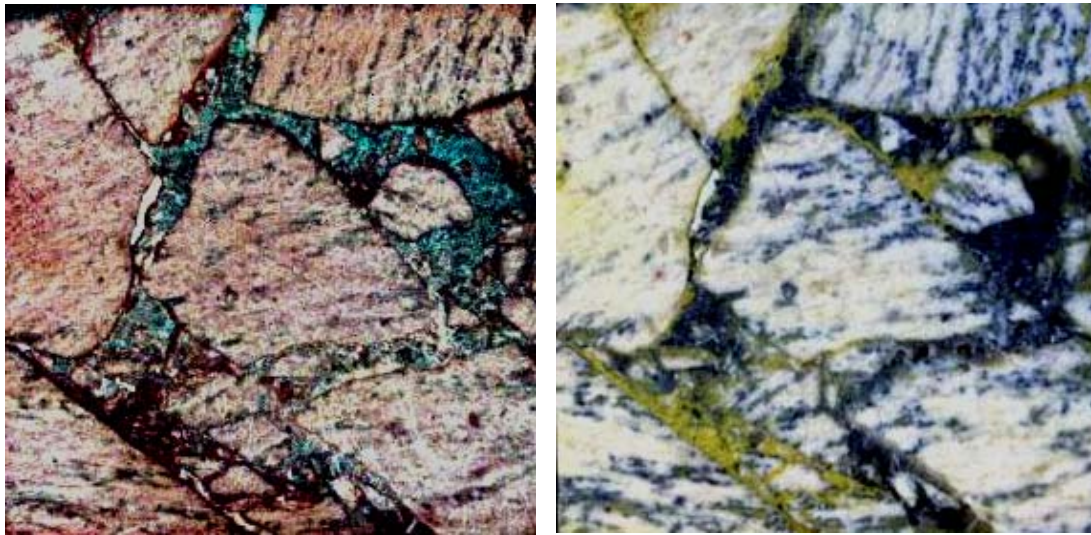


Figure 6.2. Natural-color image (left) composed of 660, 525, and 470 nm bands; and false-color image (right) composed of 1450, 1200, and 880 nm bands; displayed in red, green, and blue respectively; selected subframe shown here is 20 × 20 mm (full field is 40 × 32 mm) with a resolution of 62.5 μm/pixel. This sample was ground to a roughness similar to that provided by the Rock Abrasion Tools (RATs) on the MERs. Interpretation: Volcanic breccia. Angular clasts of a fine-grained silicic volcanic rock have been cemented by calcite and hematite. Angular shapes and poor size sorting of clasts indicate minimal transport. This, along with the uniformity of clast compositions (monolithologic), suggests deposition near the volcanic source, perhaps as an airfall tuff (lapillistone).

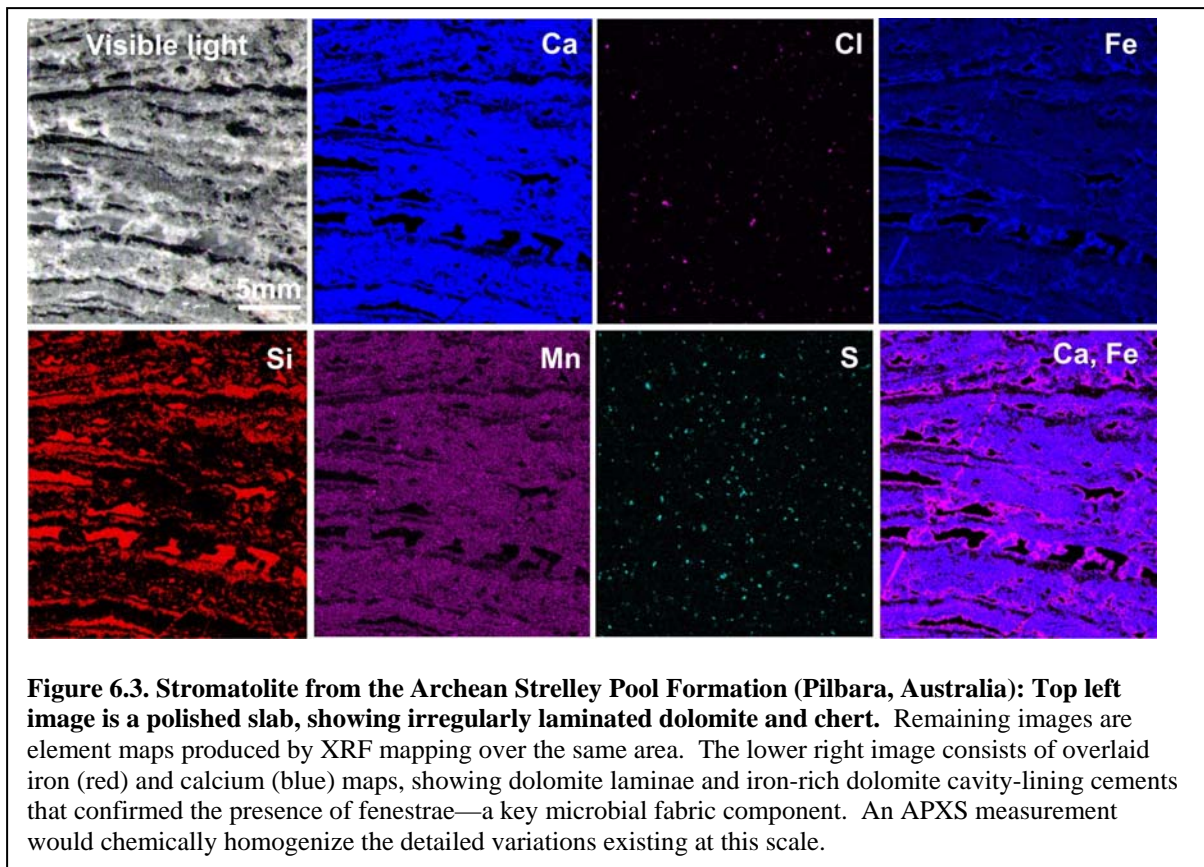
The images reveal important information about the depositional processes that formed this volcanoclastic sedimentary rock and also about the microscale aqueous environments that existed within the rock during its early postburial history. The Multispectral Microscopic Imager is estimated to have a mass of about 1.6 kg and consume ~19W peak including electronics.

6.1.2. XRF Chemical Micro-Mapper (Robotic Arm-Mounted)

X-Ray Fluorescence (XRF) chemical micromapping produces a series of high-resolution element maps showing the spatial distribution of chemical elements in rocks. These hand-lens scale maps can be digitally overlaid to reveal covariations between elements, and relationships between chemical composition and visible textures and microstructures. This information can be used to:

- Determine the mineral composition of individual grains, cements, alteration rims, fracture-fills, etc.,
- Detect otherwise cryptic features such as textural components that have the same mineralogy, but slightly different elemental composition, and
- Verify mineralogical interpretations and identify mineral types that can be difficult to constrain with other spectral techniques.

XRF micromapping is inspired by state-of-the-art bench top chemical mapping instruments. These instruments use a capillary optic (Ohzawa, 2008) to focus an X-ray beam down to a 100 μm spot. The beam is raster scanned across the sample surface while XRF spectra are rapidly acquired at close spacing, gradually building up a raster image for each element measured (e.g., Figure 6.3). Up to 14 single-element maps are acquired simultaneously, detecting elements from Na to U, over a map size of up to 10 cm \times 10 cm.



The flight instrument would also consist of a capillary focusing optic, miniature X-ray tube, detector array, and 2-D translation stage (all mounted on the arm) operated with a high voltage power supply and detector electronics (mounted in the rover body and connected via insulated cable along the rover's robotic arm). The estimated total mass of a flight X-Ray Micro-Mapper is ~ 2.5 kg, with power

consumption of ~30 W. Preliminary estimates suggest that the X-Ray Micro-Mapper could analyze a 1 cm² area of an abraded rock surface on Mars at 100 μm resolution in about three hours.

The scientific value of the technique has been validated through studies of ~3.5 billion year-old rocks containing the oldest evidence of life on Earth: element maps acquired with a commercial XGT X-ray analytical microscope reveal mineralogy and key aspects of rock fabrics that constrain palaeoenvironmental conditions, habitability, and biogenicity in Early Archean stromatolites (Figure 6.3) (Allwood et al., 2009). In the context of planetary exploration, chemical mapping would have even greater value, providing a valuable substitute for thin section petrography (a fundamental part of geological studies on Earth, but complex and resource-intensive for robotic planetary exploration). Using XRF to map covariations among elements against a backdrop of optical imagery would achieve many key objectives of thin section petrography.

6.1.3. Alpha Particle X-Ray Elemental Chemistry Instrument (Robotic Arm-Mounted)

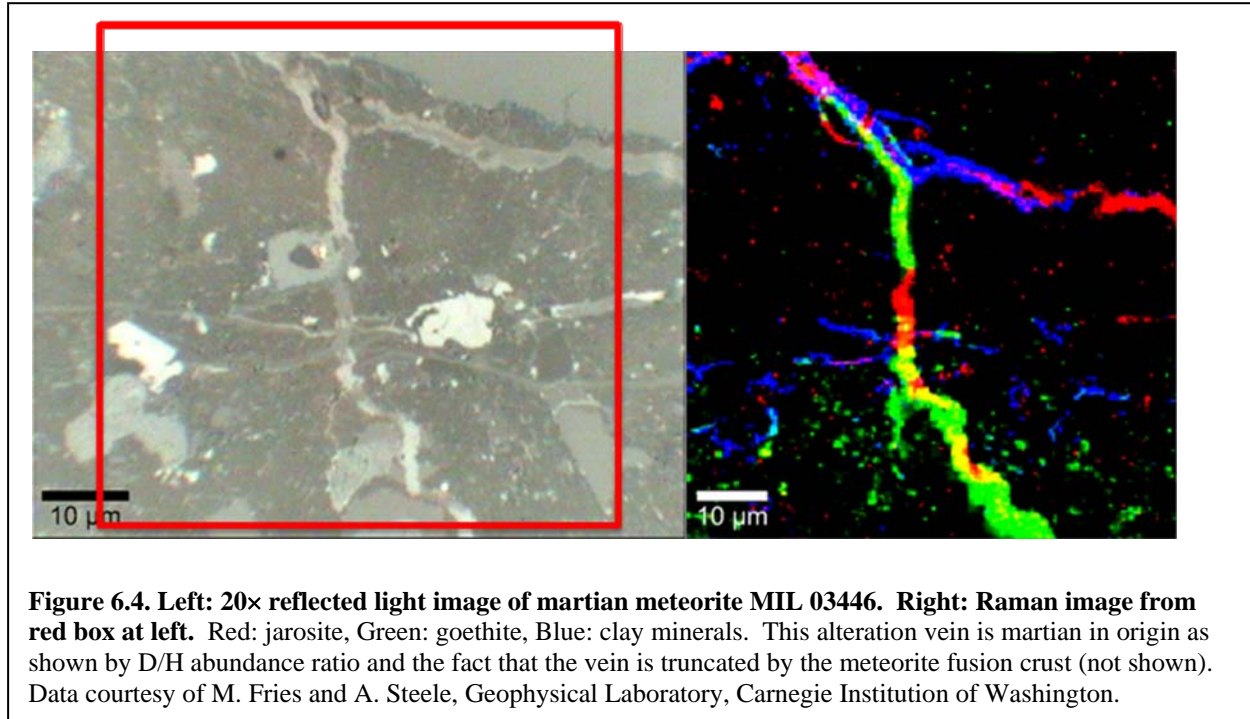
An alternative to the XRF Chemical Micro-Mapper (Section 6.1.2) is provided by an Alpha Particle X-Ray Spectrometer (APXS). An APXS provides bulk chemical analysis averaged over an area a few cm in diameter. The advantages of the APXS include flight heritage, fast analyses, and small data size.

An APXS similar to the one built for MSL could provide bulk elemental composition measurements (Na to Br) on rock or soil surface target areas ~1.7 cm in diameter, to a depth of 5 to 50 μm. The MSL APXS has significant heritage from the APXS instruments flown on Spirit and Opportunity (Rieder et al., 2003; Gellert et al., 2006, 2009). A thermoelectric cooler allows operation up to martian ambient temperatures of -5 °C. Measurements can be taken by deploying the rover's robotic arm to place the instrument's sensor head in close contact with a sample. The sensor head containing radioactive ²⁴⁴Cm sources bombards the sample with emitted alpha particles and X-rays. From the X-rays measured by the sensor head detector (equivalent to PIXE and XRF techniques), the rough abundance of major elements can be obtained in 15 minutes or a complete chemical analysis, including some trace elements, can be obtained in 2 to 3 hours requiring a total of ~ 6 W with no cooler or ~ 10 W with the cooler (only required at the highest ambient temperatures) with an instrument mass of 1.7 kg. The 10 mm² silicon drift detector can achieve a full-width at half maximum at 5.9 keV of ~140eV, and covers the X-ray energy range from 700eV to 25 keV with 1024 channels. In addition, backscatter peaks of primary X-ray radiation allow detection of bound water and carbonate at levels of around 5 wt% (Campbell et al., 2008).

6.1.4. Green Raman Imager (Robotic Arm-Mounted)

Raman spectroscopy is a point analysis method that uses energy loss from an excitation laser source due to lattice or molecular vibrations to discern the identity of the targeted material. Raman imaging is a new technique that rasters the point excitation source across an area to produce images instead of point measurements, resulting in far more information. For example, a point Raman instrument on Mars could discover jarosite but this tells us little more than we already know, namely that jarosite exists in martian mineralogy. A Raman image containing jarosite (Figure 6.4) would enable us to determine whether the jarosite exists as wind-blown fines, a weathering rind component, in a cement, in a breccia, as an alteration vein, as a constituent in a layered deposit, or as a deposit that fills vesicles, etc. (Vincenzi et al., 2007; McCubbin et al., 2009). Each of these settings can be used to describe the origin and alteration history of the target material. While commercial Raman imaging instruments are common and have achieved considerable maturity, to date no Raman imaging instrument has been developed for space flight. The Mars Microbeam Raman Spectrometer (MMRS) is the closest to this achievement (Wang et al., 2003), as it can make linear scans and was proposed as part of the Athena rover payload and was considered for, but not flown on, the MERs. Commercial instruments can image areas 100 μm² up to

multi-cm², with pixel sizes from ~1 μm² down to 360 nm². The primary limitation arises from native sample fluorescence, but there are technical means to minimize that effect. Mineral sensitivity is extraordinary, ranging from clay minerals to opaque minerals, to the full range of carbonaceous species (Schopf et al., 2002; Steele et al., 2007; Fries et al., 2009; Papineau et al., 2009) from diamond to organic compounds, and to every known silicate mineral. No sample preparation is necessary, but some surface grinding may be preferable. The flight instrument mass is estimated to be < 6 kg and the power required < 30 W including electronics with a field of view of 1 cm² and a resolution of 4 μm.



6.1.5. Deep Ultraviolet Raman/Fluorescence Mapper (Robotic Arm-Mounted)

Deep ultraviolet (DUV) Raman spectroscopy is well suited to *in situ* analysis of many carbonaceous compounds (Asher and Johnson, 1984; Storrer-Lombardi et al., 2001; Hug et al., 2006; Frosch et al., 2007; Bhartia et al., 2008). Rayleigh enhancement with deep UV excitation generates ~20 times greater signal strength than the same measurement made with a green excitation laser and greater than 100× over a red (785nm) excitation laser. Resonance Raman effects in carbonaceous compounds under UV excitation produce additional signal improvement that range up to 8 orders of magnitude (Asher and Johnson, 1984; Storrer-Lombardi et al., 2001). Examples of resonantly enhanced bonds include but are not limited to water, C-H, CN, C=O, C=C, NH_x, NO_x, SO_x, PO_x, ClO₄, and OH with sensitivities in the sub parts per million (Dudik et al., 1985; Asher et al., 1986; Burris et al., 1992; Ianoul et al., 2002). In addition to the resonance enhancements, with excitation below 260 nm, Raman and fluorescence regions do not overlap (Asher and Johnson, 1984; Frosch et al., 2007). This enables simultaneous measurement of Raman spectra and fluorescence backgrounds (Bhartia et al., 2008).

Coupling DUV Raman with DUV native fluorescence would enable characterization of biological materials as well as structure and arrangement of aromatic rings with sensitivities at the sub-part per billion (Bhartia et al., 2008; Rohde et al., 2008) (Figure 6.5). These combined datasets make it possible to map the distribution of organic compounds and water (Figure 6.6). This instrument can achieve a field-of-view of 1 cm², with spatial resolution of 10 μm, as a rover arm mounted instrument mapping at a

standoff distance of 2.5 cm. The mass and power consumption for this instrument is estimated to be ~5 kg and < 20 W including electronics.

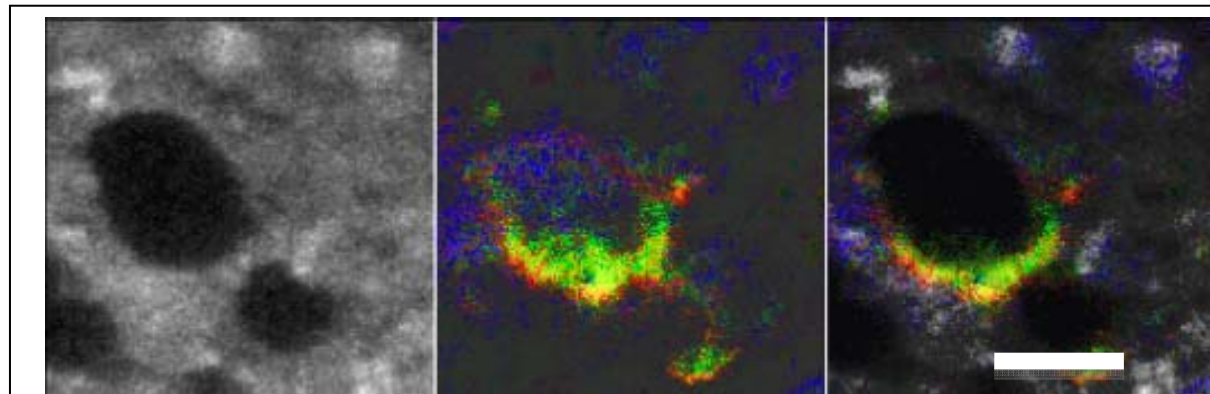


Figure 6.5. DUV (< 250 nm) excitation of native fluorescence from a basalt vesicle (dark area) from Svalbard, Norway. Left is a visible reflectance image. Center is a native fluorescence image. Fluorescence analysis (Bhartia et al., 2008) indicates the presence of 2 ring aromatics (yellow regions) as possible mantle derived organic compounds. Right is a visible and fluorescence overlay. White scale bar: 2mm. Sample courtesy of A. Steele, Geophysical Laboratory, Carnegie Institute of Washington. For further information on the geology and geochemistry of a basalt from this locality, see Steele et al. (2007).



Figure 6.6. DUV excited H₂O Raman map of an altered basalt from the Mojave desert, acquired from a 2 m standoff (image = 20.3 cm × 7.6 cm). Left: Visible reflectance image, white regions are composed of carbonates. Center: False-color map of the OH-stretch Raman band showing the distribution of hydrated minerals (magenta color) indicating extent of fluidic alteration. Right: Overlay of the reflectance and Raman map indicates carbonate deposited by aqueous transport and mixed with hydrous mineral phases. White scale bar: 5 cm.

6.1.6. Imaging Spectrometer (Mast-Mounted)

The Mast-Mounted Imaging Spectrometer is a passive instrument that operates in the visible and short-wave infrared (SWIR) portion of the spectrum to provide detailed mineral maps of the surrounding terrain and the mineral composition of specific rocks and outcrops. Spatial resolution varies with distance from the target, reaching down to a few mm at distances below 10 m (example shown in Figure 6.7). The instrument is capable of generating 360° panoramic image mosaics and providing compositional information for each pixel in the images. Its spectral range and spectral resolution are similar to those of the orbiting CRISM and OMEGA instruments, allowing extension of the orbital measurements to higher spatial resolution in addition to providing “ground truth” data. SWIR spectroscopy has proven to be highly effective in mapping aqueous alteration deposits on Mars from orbit (Noe Dobrea et al., 2009), and has been used to identify minerals such as hydrous sulfates and phyllosilicates on the martian surface (e.g., Bibring et al., 2005; Gendrin et al., 2005; Langevin et al., 2005), carbonates (Ehlmann et al., 2008), opaline silica (Milliken et al., 2008), and mineralogically complex regions with multiple types of clay minerals including iron- and aluminum-rich varieties (e.g., Bishop et al., 2008).

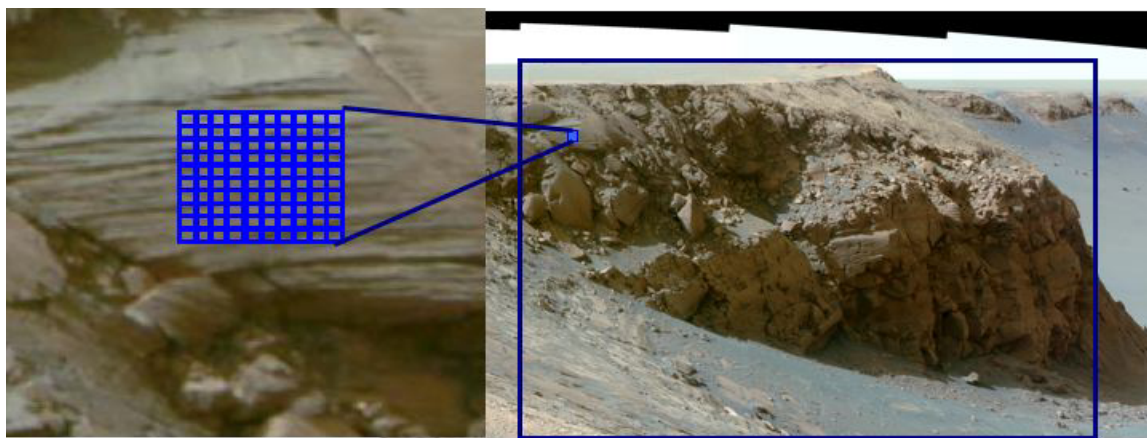


Figure 6.7 . Right image: Example color image mosaic of Cape St. Mary, a promontory on the rim of the Victoria Crater, Mars, acquired by Pancam on Opportunity rover). The observation spans $36^{\circ} \times 20^{\circ}$ (620×344 pixels). Left image: A 10×10 square pixel area is expanded, showing the ability to resolve differences within layers. Pancam image credit: NASA/JPL-Caltech/Cornell University. The Mast-Mounted Imaging Spectrometer would provide visible through short wave infrared spectra for each pixel.

This medium to low risk instrument is expected to have a 3 kg mass and power requirements of 6 W including electronics, optics, and thermal control. The instrument has no mechanisms other than the scanning in x and y provided by the mast. A single data set will typically comprise an area of 344×344 spatial pixels (1 mrad^2) with a single line field-of-view of $1 \text{ mrad} \times 20$ degrees. Each pixel is simultaneously imaged in ~ 420 spectral bands spectral bands over a range of 400-2500 nm where the spectral resolution is 5 nm.

6.2. Instrument Development

Preliminary scheduling for a mission project of this kind indicates that the instrument competition might take place in late 2012, with instrument selection about six months after that. Candidate instruments need to be at about TRL-5 or greater in order to be credibly proposed. This means that during the next two years significant instrument funding through NASA's MIDP, PIDDP, and similar programs would need to be made available to the community. Instrument competitions should include specific needs related to the proposed MAX-C mission. As discussed above, because many of the instruments of high relevance to the MAX-C mission concept are at a readiness state less than TRL-5, the definition of a straw-man payload suite, which must be done immediately for engineering trade studies, will necessarily be immature. To the extent possible, the results of early engineering trade studies should be fed back into instrument development constraints and priorities.

MAJOR FINDING: For these instruments to be mature enough to be selectable for flight (i.e., TRL of 6), a commitment must be made now and sustained for the next several years to improve the maturity of the most promising candidate instruments.

7. RELATIONSHIP TO A POTENTIAL SAMPLE RETURN CAMPAIGN

In order to analyze the relationship of the proposed MAX-C mission to the possible future return of samples from Mars, it is necessary first to consider some of the aspects of sample return. The potential sample return objectives, sample acquisition and preservation requirements and strategies, and sample

context requirements are relevant planning considerations. In Section 7.2, we discuss how the proposed MAX-C mission would fit into a larger possible mission architecture configuration. The expectation is that the potential MAX-C sample cache would be a returnable and scientifically enticing cache that the science community would be eager to see returned to Earth (Section 7.3).

7.1. Proposed Mars Sample Return Scientific Objectives and Required Measurements

7.1.1. Potential Sample Return Scientific Objectives

A potential sample return campaign would carry an unprecedented combination of cost and risk, and because of this, must return unprecedented scientific value. The value of a potential Mars sample return has been discussed in the literature for at least 30 years (see, for example, NRC, 1978, 1990a, 1990b, 1994, 1996, 2003, 2006, 2007) and the scientific rationale for returning samples has evolved over time. Early studies (e.g., NRC, 1978) emphasized the need for samples to better understand the evolution of the planet. Emphasis in the last two decades, on the other hand, has been on the search for past and present life (e.g., NASA, 1995; NRC 2007). Answering the life question (“Are we alone?”) is now one of the most important strategic drivers for NASA (NASA Strategic Plan), and the Mars Exploration Program has therefore long carried the objective “determine whether life ever arose on Mars” as one of its top priorities. Returning samples from Mars is considered essential for meeting that objective.

In accordance with these considerations, the MEPAG ND-SAG (2008) reached the following conclusions after carrying out a detailed analysis of the scientific trade space associated with the objectives and implementation options of a potential sample return campaign:

- Many scientific objectives could be achievable using a sample return campaign (11 objectives listed in MEPAG ND-SAG, 2008), depending on where it would be sent, what kinds of samples it could acquire, and in what condition they would be returned. Unfortunately, some objectives require relatively specific samples, and there is probably no single place on Mars where a suite of samples could be collected that would achieve all of these objectives. Thus, planning for a potential sample return must carefully consider the priority of its scientific objectives, the influence this prioritization has on choice of landing site, and criteria for selection of samples at that site.
- The most important scientific objectives of a potential sample return mission should relate to “the life question” (see also NRC, 2007; iMARS, 2008; MEPAG, 2009).

Because of the significance of the life question to Mars exploration, we conclude that returned samples from Mars must make a substantial contribution in that area. For many reasons, however, a significant contribution must also be made toward at least one of the other high-priority objectives that have been defined by the Mars scientific community.

FINDING: For a potential Mars sample return mission to deliver value commensurate with the cost and risk, it must address a major life-related objective as well as one or more of the major geologic objectives defined by the MEPAG ND-SAG (2008).

7.1.1. The Kinds of Samples Needed to Achieve these Objectives: Diverse, Intelligently Collected Samples

The NRC (1978) first concluded that a potential Mars sample return mission must return “an intelligently selected suite of Martian samples,” and this recommendation has been reinforced by subsequent panels ever since. A primary theme of the ND-SAG report was to emphasize the need for careful selection to ensure geologic diversity (MEPAG ND-SAG, 2008). This is especially true for addressing the life

question, because detecting and interpreting potential evidence of microbial life requires assessment of the palaeoenvironment, its habitability and biosignature preservation potential, and the relationships of potential biosignatures within the paleoenvironmental context. Moreover, the sampling should take strategic advantage of the contextual framework to allow robust testing of different hypotheses that arise. Evidence of life is not likely to be something that resides in a single sample: rather, evidence of life emerges from an assemblage of observations, strategically analyzed and integrated across all scales of observation. This is unequivocally illustrated by the challenges and spirited debate surrounding the search for Earth's earliest biosignatures (e.g. Walsh, 1972; Lowe, 1980, 1983, 1992, 1994; Walter et al., 1980; Buick et al., 1981; Awramik et al., 1983; Walter, 1983; Walsh and Lowe, 1985; Byerly et al., 1986; Schopf and Packer, 1987; Schopf, 1993, 2006; Grotzinger and Knoll, 1999; Hofmann et al., 1999; Hofmann, 2000; Ueno et al., 2001; Westall et al., 2001, 2006; Brasier et al., 2002, 2006; Van Kranendonk et al., 2003; Lindsay et al., 2003a, 2003b, 2005; Tice and Lowe, 2004; Moorbath, 2005; Allwood et al., 2006, 2009; McCollom and Seewald, 2006; Westall and Southam, 2006; Westall, 2007).

FINDING: Particularly in the case of a “signs of life” objective, a potential sample return mission should be designed to return a set of intelligently collected, diverse samples.

One advantage of returning samples is that the investigations could generate results much more definitive than those achievable by *in situ* techniques alone. This lesson has been learned over and over again by geologists working in the field on Earth. However, an extension of this lesson is that the scientific productivity of the samples would be strongly dependent on their character. For example, as pointed out by ND-SAG (2008), returning 24 identical rocks would have no more scientific value than returning one. For this reason, we introduce the concept of “outstanding samples,” or perhaps more properly, “outstanding sample suite.” On the one hand, we agree with the position (most recently summarized by NRC, 2007) that there is no such thing as “the ideal sample,” and that delaying a potential sample return campaign until it is discovered is illogical. On the other hand, even though any sample returned from Mars would be useful for some aspect of scientific inquiry, it is also true that not all samples would be equally useful for the kinds of scientific questions we are trying to answer. Moreover, the concept of a suite of samples is rooted in the premise that the differences between samples is as important, or even more so, than the absolute properties of any of them. Thus, a well-collected suite of samples would be one that represents the range of natural variability of a key martian geologic process. A couple of examples to illustrate the point are shown in Figure 7.1.

In both of the examples in Figure 7.1, there is more than one way to assemble an effective suite of samples, and equally effective suites could be collected at other nearby localities. The common point, however, is the identification of samples that span the range of natural local diversity is required in order to make effective sample selection decisions. Such samples would be more than “ordinary” and less than the “right” sample—for this we use the term “outstanding” samples. Clearly, the acquisition of a set of outstanding samples would take planning and effort.

FINDING: To meet the high expectations, a potential sample return mission should return “outstanding samples” that have the potential to generate results more definitive than those achievable *in situ* and could make a significant contribution to addressing MEPAG’s life-related scientific objectives.

Seeking signs of life demands a host of scientific investigations that would yield important *in situ* results in their own right. Furthermore, such results would also provide essential information for addressing other high-priority scientific objectives. Thus, very little scientific trade-off is required between simultaneously optimizing feed-forward to a “signs of life” potential sample return campaign and conducting significant *in situ* science in multiple high priority research areas.

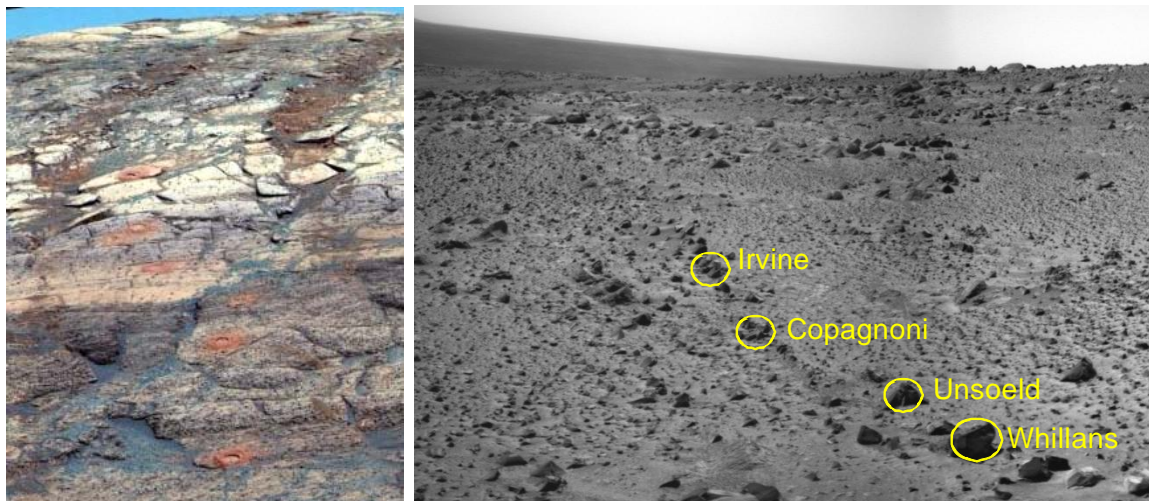


Figure 7.1. Two examples (S.W. Squyres , writ. comm., 2008) highlighting the importance of sample selection tools in understanding the range of natural variation, which is crucial in assembling a suite of outstanding samples. (Left) False-color rendering of a Pancam image mosaic from Opportunity rover on Sol 173 (July 19, 2004). The view, looking back up toward the rim of Endurance crater, shows the rover’s tracks and the first seven holes made by the Rock Abrasion Tool as the rover moved down layers of exposed rock. Image credit: NASA/JPL-Caltech/Cornell. (Right) A new type of basalt was detected with Spirit rover’s Mini-TES at the summit of Husband Hill (McSween et al., 2006), at this location shown in a Navcam mosaic from Sol 598. The rock named Irvine, which was part of an aligned set of similar rocks (some of which are circled in yellow), was more closely examined with instruments on the robotic arm. Characterization of the difference between the alkaline basalt Irvine and other more common subalkaline basalts allowed interpretation of the liquid line of descent—this would not have been possible if this type of sample had not been recognized. In addition to the need for macroscopic target selection, sample acquisition decision-making would also need to incorporate observations from finer scale, such as those in Figure 6.1 and possibly also the other figures in Section 6. Image credit: NASA/JPL-Caltech.

7.1.2. Measurements Needed to Make Sample Selection Decisions and to Document Sample Context

As noted by the MEPAG ND-SAG (2008), in order to interpret analytical results obtained from potential returned samples, the geologic context of the landing site should be fully documented. Such documentation should include mapping bedrock and other surficial rocks, mineralogy, geochemistry, and petrology. Thus any potential sample suite must be characterized *in situ* and be designed to leverage the geological context to aid in the interpretation of eventual Earth-based laboratory analyses. Achieving these requirements would substantially influence landing site selection and rover operation protocols. The importance of access to outcrops would necessitate either significant traverse capability or hazard avoidance during descent (see Section 10.2).

The MEPAG ND-SAG (2008) proposed two instrument suites for a potential sample return mission; one designed for a mission sent to a previously visited site and the other for a mission going to a new site (Table 7.1). The MRR-SAG agrees that, at the bare minimum, the potential sample acquisition rover must make the ND-SAG’s minimum observations for a new site:

- (1) Color stereo imaging
- (2) Microscopic imaging
- (3) Elemental and mineralogical determinations
- (4) Detection of reduced carbon
- (5) Ability to remove weathered and/or dust-coated surfaces (i.e., an abrasion tool)

The ND-SAG noted that it is theoretically possible for a potential sampling rover that revisits a previously explored route at a well-characterized site to carry reduced instrumentation (indicated by the pink boxes in Table 7.1). However, this would mean that the potential rover might need to revisit exact positions, and possibly the same RAT holes, if the compelling rock features are difficult to find and document with just cameras (as the ND-SAG recommended). Since such a mission would have to rely on cameras for all of its selection and documentation of samples, the risk of not being able to reoccupy exact locations that were characterized by the previous (MER or MSL) mission is a potentially crucial vulnerability with extremely negative consequences to the scientific return. The MRR-SAG concluded that the same payload would be required, whether the potential sample acquisition rover is sent to a new or a previously-visited site (Table 7.1, right two columns). In addition, the MRR-SAG updated Table 7.1 to indicate that the mineralogy information should assist with both the location of samples from a distance (purple boxes in Table 7.1) and the characterization of samples at higher spatial resolution. The ND-SAG did not specify the exact nature of the recommended required mineralogy measurements, other than the need to differentiate rock types and effects of natural processes.

Table 7.1. Recommended required instrumentation for a potential caching rover that is directed to a new landing site or to a previously-visited site. The left-hand part of this table was developed by ND-SAG (2008; Table 6). The MRR-SAG reached consensus on the right two columns, identifying the same payload that would be required for a new site as for a previously-visited site.

What would be needed	Measurement	ND-SAG		MRR-SAG	
		New	Prev.	New	Prev.
Ability to locate samples	Color stereo imagery	YES	YES	YES	YES
	Remote mineralogy			YES	YES
Ability to determine fine rock textures (grain size, crystal morphology), detailed context	Microscopic imagery	YES	YES	YES	YES
Ability to differentiate rock types, effects of different natural processes	Mineralogy	YES	NO	YES	YES
Ability to differentiate rock types, effects of different natural processes	Bulk elemental abundance	YES	NO	YES	YES
Ability to detect organic carbon	Organic carbon detection	YES	NO	YES	YES
Ability to remove weathered or dust-coated surface and see unweathered rock	Abrasion tool	YES	NO	YES	YES

FINDING: The potential rover needed to do scientific sample selection, acquisition, and documentation for potential return to Earth should have similar measurement capabilities, whether it is sent to an area that has been previously visited, or to a new unexplored site.

The MRR-SAG notes that this recommended minimum required set of observations would be greatly improved with various “upgrades,” if they could be accommodated. Such upgrades would include the capability to evaluate chemistry and mineralogy of small-scale features and capability of evaluating constituents of interest to astrobiology in addition to reduced carbon (such as N, S, and biosignatures). Based on experience from MER, where the science team had difficulties inferring orientation of underground bedding, the inclusion of a subsurface sounding instrument such as ground-penetrating radar would also add valuable context.

The potential sample acquisition rover should carefully document the context of its collected samples and should be robust against any challenges impinging on the proposed scientific objectives. For example, several likely scenarios exist where the potential sample acquisition rover might be unable to access and sample the exact spot(s) where MSL might make compelling discoveries. Indeed, a well-equipped potential sample acquisition rover could make its own novel discoveries at a MER or MSL site. The ability of a potential sample acquisition rover to stand alone in its ability to execute a scientifically valuable mission would also add considerable robustness to a potential sample return campaign. Of course, future MER or MSL discoveries could help to optimize the measurement capabilities of a sample acquisition rover and thereby enhance even further the scientific return of the overall potential sample return campaign.

FINDING: 1) The potential sample acquisition rover must provide the data needed to find and select samples, and to establish their context over a wide range of scales. 2) The baseline instrument package might need to be modified, depending on the specifics of what the MERs or MSL find, if the potential sample acquisition rover returns to one of those previously visited sites.

7.2. How the Proposed MAX-C Mission Fits in a Potential 3-Element Sample Return Campaign

Given current understanding of celestial dynamics and engineering approaches to optimize spacecraft design, it is widely accepted that the return of samples from Mars would involve a potential campaign of multiple missions (see e.g., iMARS, 2008; Borg et al., 2009). The proposed MAX-C mission would be intended to be the first step of a potential 3-element campaign (Figure 7.2), followed by another potential mission (MSR-L) carrying a small rover that would fetch the proposed MAX-C cache (i.e., surface rendezvous) and also carrying a Mars Ascent Vehicle (MAV) capable of launching a container holding the proposed cache into orbit for rendezvous with an orbiter mission. A 3-element

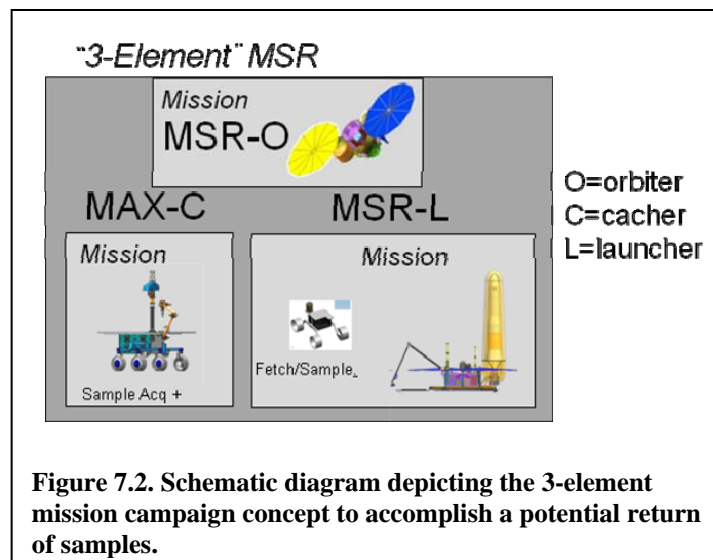


Figure 7.2. Schematic diagram depicting the 3-element mission campaign concept to accomplish a potential return of samples.

architecture would offer some major financial advantages in the form of smoothing future budget peaks for the Mars flight program (e.g., Li, 2009).

7.2.1. Considerations Related to a Potential 3-Element Campaign

Exploring a site prior to sending the potential sample return system (i.e., lander and MAV) would reduce both engineering and scientific risk for the overall potential sample return campaign. Many scientists and engineers have previously concluded that it would be too risky to send the mission that would land the MAV to a site other than one that has been previously visited (MacPherson et al., 2005; discussions at the MSR workshop in Albuquerque, May, 2008), and after extensive debate within the team, the MRR-SAG strongly endorses that conclusion.

FINDING. In order for a potential sample return campaign to be of acceptable risk (both science and engineering), the potential MSR-Lander mission should be sent to a site previously explored by a rover or lander.

We would know that the samples exist, are retrievable, and are of sufficient scientific interest before committing to sending the potential lander mission with the MAV. Moreover, we would have completed exploration and documentation of the geological context with a payload optimized for science. Sending the MAV in a launch opportunity after the proposed MAX-C rover would allow it to be launched with a more modest fetch rover (requiring a minimal payload and briefer surface operations time).

For the potential 3-element approach, the MAV would not be put “at risk” until after the cache has been prepared, thus making it more likely that the proposed MAX-C rover would be allowed visit a site that has not been previously ground-truthed. Allowing a broader range of landing sites to be considered is a significant scientific benefit of a potential 3-element campaign (as discussed in Section 9.2). The intention would be to fly the MAV in a follow-on launch opportunity, but the go/no-go decision could be made after the proposed MAX-C mission. In a 3-element campaign, after arrival on Mars, the proposed MAX-C rover would likely have plenty of operations time (depending on rover lifetime and which launch opportunity would be used for the mission carrying the MAV) to collect a thoughtfully selected, thoroughly documented, diverse set of samples from a well-characterized geologic setting.

FINDING: A potential 3-element MSR campaign would result in great simplification of the MSR-Lander mission. By reducing the number of miracles that mission would require, the overall campaign would be more technically feasible.

In a 3-element campaign, the proposed MAX-C rover mission would be required to make quality sample selection decisions, to document the context of the samples chosen, and to actually acquire and cache the samples chosen. The instruments necessary to provide the informational basis for these decisions would also need to be present to achieve the *in situ* objectives.

In summary, the proposed MAX-C rover could benefit the potential sample return campaign in the following ways:

1. Developing and accomplishing rock coring and encapsulation.
2. Assembling a cache containing sample suites acquired from a diverse set of sampling locations.
3. Accomplishing #1 and #2 above, consistent with sample return planetary protection and contamination control requirements (Section 16, Appendix E).
4. Preparing and operating a new generation of instruments optimized for sample selection and site characterization.
5. Further verifying the performance of the MSL EDL system and improving targeting accuracy. This would also benefit the later potential mission carrying the MAV and fetch rover.

FINDING: The proposed MAX-C mission would help prepare for a potential sample return in at least five critical areas – thereby significantly reducing the “number of miracles” needed for an overall sample return campaign.

On the other hand, sample caching would consume critical mission resources (e.g., money, mass, and surface operation time) that could have been used for *in situ* scientific operations. For example, a drill on an instrument arm would increase the vibration isolation design requirements for the scientific instruments on the arm.

FINDING: Caching samples on the proposed MAX-C mission would be of major engineering benefit to potential sample return, but this would come at a cost to *in situ* science of the proposed MAX-C mission. The importance of a sample return makes this trade worthwhile.

7.2.2. Possible Risk Reduction Engineering Measurements in a Potential 3-Element Campaign

By virtue of the potential 3-element campaign, the proposed MAX-C rover might be able to carry out certain specific tests that would buy down engineering risks for the follow-on parts of the campaign. We present one example related to electrical fields, but encourage further discussion by future planning teams. Theoretical predictions and laboratory simulations suggest that electrostatic charging could be a serious risk to the launch of a MAV from the martian surface, but scientists do not have sufficient information to confirm the magnitude of the risk (Melnik and Parrot, 1998; Farrell et al., 1999; Farrell and Desch, 2001; Michael et al., 2008). Electrical discharge in dust storms (Farrell et al., 1999) and rocket-triggered lightning along the exhaust trail of a MAV during ascent from Mars (MEPAG HEM-SAG, 2008) are a possible concern. The potential MAX-C rover could include a device that monitors electric fields (e.g., Farrell et al., 1999; Berthelier et al., 2000), in order to determine the magnitude of the risk and to affect the design of the MAV so that it would be robust in the local martian conditions. An electric field probe with a mass of ~ 0.5 kg requiring ~ 1 W has some MIDP heritage (MEPAG HEM-SAG, 2008). Future design teams should determine the specific nature of the electric field information needed to significantly reduce risk of the MAV launch, and assess the feasibility of achieving and accommodating those measurements with an *in situ* instrument.

There could be other measurements like this, or engineering design implementations of the proposed MAX-C mission that should be considered, that would reduce the cost and risk of the other missions that are part of the overall potential sample return campaign. This is left to future study groups and engineering teams to determine.

7.3. The Proposed MAX-C Sample Cache – Intent to Return

It is not possible to know in advance what would be discovered at any individual landing site on Mars. Our orbital data sets are of very high quality, but we know from the experience at both MER sites that orbital data can give incomplete representations of the surface geology. For example, at the Opportunity site, the orbital data show the presence of hematite but not sulfate, and in actual fact, both can be detected from the ground. However, a crucial point is that this committee has concluded that to within reasonable levels of confidence, a high-quality landing site for the assembly of a sample cache can be selected from orbital data, and the intent is that the samples selected at that site would actually be returned if the follow-up MSR mission were approved. It would be unwise to formally make this decision before the potential sample collection and caching missions take place, and it is possible to envision scenarios in which the proposed MAX-C cache would end up with lower than expected scientific priority (for example, if the rover fails to access certain high-priority sampling targets). However, the baseline intention is that the proposed MAX-C cache would be returned, and mission planning should be carried out on this basis.

8. CONSENSUS MISSION VISION

As discussed at the recent (July 29-30, 2009) MEPAG meeting at Brown University (<http://mepag.jpl.nasa.gov/meeting/jul-09/>), the Mars Exploration Program appears to be moving forward from a strategy of “follow the water” and examining habitable environments towards one of “seek signs of life.” Also included in the strategy is preparation for a potential Mars sample return. To further focus the proposed MAX-C mission toward a single concept, the MRR-SAG considered how the investigations and measurements proposed for the top three concept missions meet the overall vision of a mission to the martian surface that would: 1) have the *in situ* scientific exploration capability to respond to discoveries by prior landers or orbital mapping missions, 2) be able to collect, document, and cache samples for potential return to Earth by a potential future mission, 3) be a key stepping stone to seeking signs of life on Mars, and 4) do all this within the constraints of a rover intermediate in size to MER and MSL. Additionally, the MAX-C mission concept must take into account areas in which it would complement, and be complemented by, ESA’s ExoMars mission.

8.1. Consensus Mission Concept

As described in Sections 6 and 7.1, the measurements needed to achieve the proposed *in situ* objectives are the same measurements needed to select samples for potential return to Earth, and to document their context.

MAJOR FINDING: The instruments needed to achieve the proposed *in situ* objectives are the same instruments needed to select samples for potential return to Earth, and to document their context. Because of the compelling commonalities, it makes sense to merge these two purposes into one mission.

This consensus mission concept has recommended objectives consisting of three components:

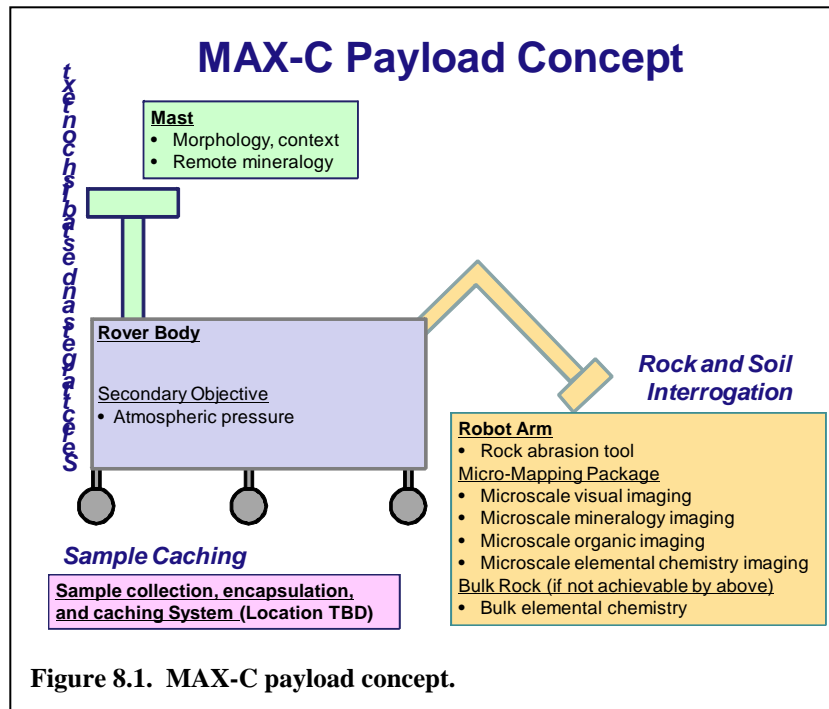
1. A set of primary objectives related to the exploration of a site on Mars. Given current scientific priorities, the proposed rover would need to visit a site with high preservation potential for physical and chemical biosignatures, and at that site, achieve the following primary objectives: a) evaluate paleoenvironmental conditions, b) characterize, *in situ*, the potential for the preservation of biotic or prebiotic signatures, and c) access a sequence of geological units in a search for evidence of past life and/or prebiotic chemistry. Note that steps a) and b) above are not the sort of thing that can be done once for the planet, and then count the investigation as complete—these activities would need to be done at every site where the potential signs of life are being investigated.
2. A primary objective to collect, document, and package in a manner suitable for return to Earth by a potential future mission at least some of the samples that would be needed to achieve the scientific objectives of a sample return mission. These samples should include some of the rocks that contain the essential evidence for the interpretations reached as part of Objective #1 above, but would also certainly include additional types of samples. As documented by ND-SAG (2008), a potential sample return would have important objectives beyond those related to the life goals, and multiple sample types would be implied, including samples of rock, soil, and atmosphere. It is yet to be determined if the proposed MAX-C mission should be designed to collect rock samples only, or if it should also collect soil samples (it might be possible to collect soil samples using the proposed mission that would carry the MAV).
3. At least one secondary scientific objective, the highest priority of which is related to measuring the surface atmospheric pressure as a function of time.

SUMMARY OF SCIENTIFIC OBJECTIVES PROPOSED FOR THE MAX-C MISSION CONCEPT:

1. **Primary Scientific Objectives:** At a site interpreted to represent high habitability potential, and with high preservation potential for physical and chemical biosignatures:
 - evaluate paleoenvironmental conditions
 - characterize the potential for the preservation of biotic or prebiotic signatures
 - access multiple sequences of geological units in a search for possible evidence of ancient life and/or prebiotic chemistry
2. Samples necessary to achieve the proposed scientific objectives of the potential future sample return mission would be collected, documented, and packaged in a manner suitable for potential return to Earth.
3. **Secondary Scientific Objective:** Address the need for long-term atmospheric pressure data from the martian surface.

In summary, the proposed MAX-C mission should provide insight into the paleoenvironment of the landing site to help constrain the conditions in which life might have evolved on Mars. Visiting terrains representing key periods in martian history (e.g., the early Noachian, or the Noachian-Hesperian boundary) could enable investigation of a prebiotic environment or an environment representing a period when Mars' climate and geology might have been in transition, affecting, for better or worse, the development of primitive cellular

life. Investigation of an astrobiology-relevant environment represented by a novel terrain not previously explored could permit tests of hypotheses relating to life in certain types of compositional or geomorphological environments. Detailed characterization of the geology of the landing site is critical to our understanding of conditions that may have enabled or challenged the development of life and/or that might have context that would guide the search for evidence of ancient life and/or prebiotic chemistry within the landing site region and more broadly across Mars. The concept of the payload needed to achieve all of the objectives, including caching samples, is summarized in Figure 8.1.



With respect to potential sample return, the proposed MAX-C mission could contribute greatly to our preparedness by caching samples, conducting site characterization (accomplished in large part via the primary *in situ* scientific objectives), and demonstrating key capabilities such as sample acquisition and manipulation, sample encapsulation, and canister loading, and planetary protection and contamination control. Inclusion of these scientific approaches and technological components on the proposed MAX-C mission could substantially reduce the risks associated with sample return and enhance the quality and

value of the science and technology required for a follow-on potential sample return mission, through early demonstration of sample acquisition and storage capabilities.

9. CONSIDERATIONS RELATED TO LANDING SITE SELECTION

In this section, the possible implications of novel discoveries by preceding missions on the design and implementation of the proposed MAX-C mission are considered, and a strategy is revealed for selecting a site that could bolster the scientific return of a potential sample return mission.

Discoveries by preceding orbiters and landers could impact the execution of the proposed MAX-C mission in several important ways. For instance, a compelling discovery at a particular locality would clearly impact the proposed MAX-C site selection process. Furthermore, the particular features identified at such a site might influence the selection of scientific instruments that would be required to perform the key types of measurements at the site. Geographical and other attributes of a landing site could influence the engineering design of the spacecraft. Possibilities such as these require consideration for how a future mission might adapt to such discoveries. Another consideration should be that if the proposed MAX-C mission is sent to a previously visited site, then Mars exploration resources would become heavily concentrated at that single site, thereby potentially reducing (or slowing) our efforts to better understand global martian geological diversity and character of diverse habitable environments.

FINDING: The best way to evaluate the multiple candidate sites from which to consider returning samples is via an open landing site selection competition with sample return selection criteria. A mission such as the proposed MAX-C presents the first opportunity to evaluate new high-potential sites via such a competition.

9.1. Discoveries Potentially Affecting Landing Site Selection

Site selection is centrally important for pursuing key scientific objectives by reading a well-preserved geologic record of ancient planetary processes and environments. Site selection is particularly critical for astrobiology, given the challenges associated with locating evidence of life on Mars, which might be akin to “finding needles [biosignatures] in a haystack [the vast martian surface].” Recent discoveries have revealed many different types of sites that were (or are) potentially habitable and which might preserve evidence of life. Each of these types must be evaluated to determine its potential value as an exploration target. For example, in the search for evidence of past environments and life, each of the following key questions sets the stage for addressing the question that follows it: Was a particular local environment habitable sometime in the past? If so, did local conditions favor the preservation of

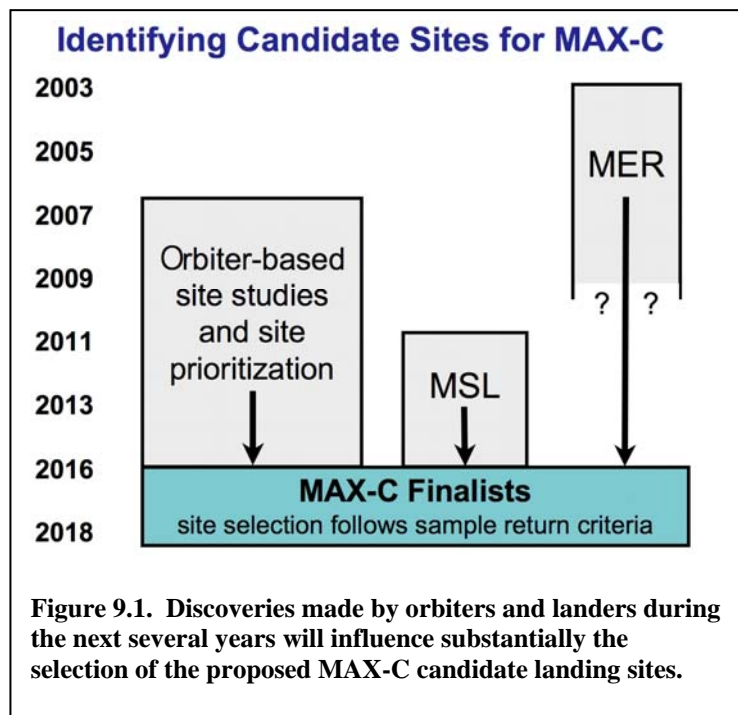


Figure 9.1. Discoveries made by orbiters and landers during the next several years will influence substantially the selection of the proposed MAX-C candidate landing sites.

evidence of environments and life? If so, are any organic compounds or other potential biosignatures present? If so, does the evidence indicate specifically that at least some chemical species, isotopic patterns, minerals, rock textures, or gaseous species probably originated from Martian life and that an abiotic origin is unlikely? Findings by the Mars orbiters and landers that precede the proposed MAX-C mission would enhance the potential MAX-C site selection process (Figure 9.1) and optimize the spacecraft design and scientific payload.

9.1.1. Orbiters

Recent remote sensing observations illustrate how an ongoing orbital campaign will help to evaluate candidate sites with regard to habitability and the potential preservation of a record of past environments and life. Minerals associated with aqueous processes occur in perhaps nine or more classes of deposits characterized by distinct mineral assemblages, morphologies, and geologic settings (Murchie et al., 2009). Phyllosilicates appear in numerous different settings, including the following: compositionally layered strata that are hundreds of meters thick and overlie eroded Noachian terrains, lower layers of depositional fans within craters, potential chloride-rich deposits on inter-crater plains, and deep bedrock exposures in thousands of craters (e.g., Schwenzer et al., 2009) and escarpments. Carbonates appear in thin unit(s) along the western margin of the Isidis basin. Hydrated silica accompanies hydrated sulfates in thin-layered deposits in Valles Marineris. Hydrated sulfates and crystalline ferric minerals co-occur in thick, layered deposits in Terra Meridiani and in Valles Marineris. Sulfates, ferric minerals, and kaolinite appear in deposits within some highland craters. While these discoveries exemplify successful outcomes of the Mars exploration theme “Follow the Water,” additional orbital observations would be required to determine which of these numerous localities has the greatest probability of supporting life in the past and preserving an accessible biological record.

Assemblages of minerals formed in ancient environments frequently can indicate whether an environment provided the requirements to sustain life including essential nutrients, biochemically useful energy, and liquid water with a sufficiently high chemical activity to sustain life. The suites of minerals that have been detected to date indicate a range of soluble cations, pH, Eh, and water activities (Murchie et al., 2009). When combined with chemical modeling, these observations provide a basis for constraining the pH and water activities of their environments of formation (Tosca et al., 2008). For example, most smectite clays form in near-neutral waters, whereas kaolinite and hydrated silica can also form under weakly acidic conditions. Carbonates typically form in weakly alkaline environments and precipitate at water activity values that can sustain microbial life as we know it. Accordingly, deposits that are probably Noachian age and contain phyllosilicates and carbonates apparently formed in environments having pH and water activity values consistent with habitable conditions (Murchie et al., 2009). Phyllosilicates in ancient plains sediments appear to be dominantly detrital and also lack evidence for sulfates or carbonates, consistent with the possibility that the water activity might have been high. Phyllosilicates that lie deeper in the crust and that have been exhumed locally probably formed in neutral to mildly acidic pH conditions. Orbiters have not yet detected mineralogical evidence indicating that these deposits formed in environments having high salinities.

In contrast, late Noachian and younger evaporite deposits may have formed in water environments that were marginally habitable at best due to low water activity, at least at the time when their most soluble salt components were precipitated. The Meridiani layered deposits at the Opportunity landing site contain highly soluble magnesium sulfates and jarosite and thus apparently formed in waters that were both acidic and highly saline (Knoll et al., 2005; Tosca et al., 2008). The presence in some intra-crater phyllosilicate deposits of hydrated Fe- and Mg-sulfates and the acid sulfate alunite indicate extreme salinities and low pH. Monohydrated Fe and Mg sulfates in some Valles Marineris deposits precipitated from brines whose water activities were perhaps too low to sustain active metabolism. In contrast, gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is estimated to precipitate from martian brines whose water activities were higher (Tosca et al., 2008) and

therefore might have sustained biological activity. Occurrences of hydrated silica might have been less saline and only mildly acidic (Murchie et al., 2009).

Potential visible, near-infrared, and mid-infrared orbital observations will clarify the relative merits of these sites to the extent that investigators can test the multiple hypotheses for the origins of aqueous mineral-bearing deposits. Such efforts will provide additional constraints on the habitability of their depositional environments. Any such insights would impact substantially the potential MAX-C site selection process. The potential future Trace Gas Mission (Smith et al., 2009a) might also provide information of interest to the MAX-C mission concept, although MAX-C, as proposed in this report, would be focused on the search for signs of life in ancient rocks.

Also critically important is the extent to which geologic deposits have preserved key information about the ancient habitable environment in which they formed. Fossilization processes are intimately tied to the physical, chemical and biological conditions that accompany the formation and long-term persistence of geologic deposits (Farmer and Des Marais, 1999). For example, chemically reducing conditions are better than oxidizing conditions in promoting the preservation of sedimentary organic matter. On Earth, minerals differ in their effectiveness as agents of preservation. Phyllosilicates and sulfates are excellent for preserving organic compounds and isotopic biosignatures but they are less effective for preserving morphological fossils. Phyllosilicates can enhance the retention of organic compounds by binding molecules to charged mineral surfaces and by incorporating them into mineral structures as interlayer cations (Keil et al., 1994; Kennedy et al., 2002; Wattel-Koekkoek, 2003; Mayer et al., 2004). Silica, and to a lesser extent carbonates, can preserve all types of biosignatures. Microbial fossils can be preserved by entombment in fine-grained mineral precipitates, such as silica, phosphate, carbonate, or metallic oxides and sulfides. Sedimentary precipitates like silicate and phosphate minerals can become very chemically stable and thus have very long residence times in Earth's crust. These minerals host the best-preserved microbial fossils in Earth's early geologic record.

Orbital observations of the abundance and geologic context of minerals such as these could support a prioritization of candidate MAX-C landing sites regarding their potential to have preserved an accessible record of ancient habitable environments. The numerous promising sites that have already been identified are widely distributed across a range of geographic locations and elevations. Further acquisition and analysis of orbiter data is needed to ensure a set of good choices for possible near-future landed missions.

MAJOR FINDING: An ongoing program of orbital observations would be essential to provide a robust site selection process for the proposed MAX-C mission.

9.1.2. Landers

Landers provide more detailed and precise analyses of particular sites than is possible from orbital observations, and make it possible to address questions such as: Did environmental conditions at the site indeed favor habitability and preservation of a record? If so, are any organic compounds or other potential biosignatures present? If so, does the evidence indicate specifically that at least some chemical species, isotopic patterns, minerals, rock textures, or gaseous species probably originated from Martian life and that an abiotic origin is unlikely?

The Mars Science Laboratory (MSL) mission is very well equipped to address these astrobiology questions as well as additional key objectives that address geologic and climate history. Efforts by MSL to map the distribution of such minerals at various spatial scales will influence substantially the way phyllosilicates, sulfates, and silica are viewed as indicators of aqueous activity and habitability and also as preservation media for biosignatures. The findings from MSL could, in turn, significantly impact

potential future mission scientific objectives, the development of flight instruments needed for sample selection, and the choice of a specific landing site for potential sample return.

Given the care of the MSL site selection process and the great potential for MSL discoveries, the MSL site might become one of the finalists for the proposed MAX-C mission, although a potential sample return would have a wider range of scientific objectives than MSL. It is likely that discoveries from orbit would also provide compelling competing sites to the finalists. Selecting a new location would broaden the diversity of explored astrobiology-relevant environments by visiting a site that is both promising and qualitatively distinct from previously visited sites.

That said, MSL's substantial capabilities and its "front row seat" location on the ground will greatly enhance its prospects for achieving compelling discoveries (see Table 9.1). MSL should confirm, at a level of confidence unachievable from orbit, whether a habitable environment indeed existed at some time in the past and whether the depositional conditions favored good preservation of information about that environment. Mineral assemblages might indicate that fluids once existed and had water activities high enough to sustain active metabolism.

MSL might find possible evidence of prebiotic chemistry or life (Table 9.1). Organic materials could have molecular compositions that are either meteoritic or indigenous to Mars and having either an abiological or biological origin. MSL might find isotopically light carbon or sulfur in minerals or organic matter.

Even more compelling would be probable evidence of prebiotic chemistry or life. Examples include organic compounds having compositions that are distinctly different from meteoritic materials and/or resemble microbial organic constituents on Earth. Microscale sedimentary fabrics and shapes also could suggest biological origins. Discrete cohesive organic layers might resemble the remains of microbial biofilms. Sedimentary fabrics might indicate stromatolites or microbialite-like structures. And patterns of stable isotopic abundances in combination with petrographic observations indicating a biological origin would be highly significant.

One very specific hypothetical MSL mission scenario illustrates the case where the potential MAX-C site selection process might consider the MSL site and additional sites identified from orbit. For example, MSL finds well-preserved deposits from a past habitable environment and these deposits contain organic matter of indeterminate origin(s). These findings would be "possible evidence of life" but meteoritic organic compounds could not be excluded. In this scenario, the site would be designated a "finalist" for the proposed MAX-C mission, but if orbital observations have also identified other as-yet unvisited localities that are highly promising, these would also be designated as finalists.

In another "possible evidence of life" hypothetical scenario, MSL explores a cross section of materials that orbital observations indicate were deposited in aqueous environments. The rover only reaches phyllosilicate deposits shortly before the end of the mission and organic compounds of possible martian origin are finally discovered. Assessment of orbital imagery has revealed an even stronger connection between these types of phyllosilicates and long-lived liquid water on the Martian surface. Such observations would warrant designating this as a potential "MAX-C finalist site."

Table 9.1. Examples of significant observations that might compel the selection of a site for the proposed MAX-C mission.

Lander Observations	
Example observations suggesting site is favorable for habitability and/or preservation	<ul style="list-style-type: none"> (1) Evidence from orbit suggesting potentially habitable conditions is confirmed <i>in situ</i> to have been a favorable environment (2) Minerals that indicate liquid water (3) Signs of conditions favoring biosignature preservation: signs of early mineralization (4) Minerals detected indicate reducing conditions
Example observations of possible evidence of life or prebiotic chemistry	<ul style="list-style-type: none"> (1) Organic materials with molecular composition that could be meteoritic or indigenous with an abiological or biological origin. (2) Isotopically light sulfur or carbon, etc. in minerals
Example observations of probable evidence of life or prebiotic chemistry	<ul style="list-style-type: none"> (1) Organic materials with composition distinct from meteoritic organics (2) "Complex" organic material with overall composition similar to microbial organics on Earth (3) Ancient organic deposits with microbial mat-like characteristics (e.g., cohesive, discrete layers) (4) Isotopic fractionation patterns with petrographic/petrologic observations suggesting primary, possibly biological origin (5) Stromatolitic or microbialite-like structures
Orbiter Observations	
Example observations suggesting site suitable for habitability	<ul style="list-style-type: none"> (1) Morphologic features indicating aqueous transport and aqueous sedimentation (2) Minerals that indicate extended activity of liquid water (3) Evidence of a hydrothermal system (4) High diversity of deposits favorable for habitability (e.g., phyllosilicates, silica, carbonates, sulfates)
Example observations of enhanced preservation of any physical and chemical biosignature	<ul style="list-style-type: none"> (1) Evidence of sustained subaqueous sedimentation or loess/paleosol development (2) Layered deposits with conspicuous lateral continuity (3) Minerals indicating reducing conditions

Remote sensing observations can also have “possible evidence of life” scenarios. For example, a spacecraft corroborates the detection of atmospheric methane and demonstrates that higher methane concentrations appear to originate from a region that harbored ultramafic rocks, serpentine, and other evidence of aqueous alteration. Such a discovery might make this region a “finalist site.”

A “probable evidence of life” scenario occurs if MSL confirms that the site has preserved a record of a past habitable environment and the spacecraft also discovers martian organic matter and possibly additional features for which martian life is the most probable source. Although such evidence might not yet provide proof of past martian life, it would provide a compelling argument that a potential sample return mission should go there in order to obtain potentially compelling evidence in Earth-based laboratories. In this scenario, the proposed MAX-C mission would likely be sent to the MSL site.

The MERs are still continuing their investigations, and one of them may yet encounter some new compelling deposits with chemical, mineralogical, and textural characteristics that compels us to make it a potential MAX-C “finalist site.” The MER payload capabilities are limited compared to the MSL rover’s, but we should leave open the possibility for new discoveries, as indicated in Figure 9.1.

However, sending the proposed MAX-C mission to a previously visited site would reduce the range of geological environments visited. Mars exploration resources would be concentrated at a single site, thereby potentially reducing (or at least slowing) our efforts to better understand global martian geological diversity of habitable environments. Finally, a requirement to return to a previous site would preclude a potential sample return mission from visiting a compelling new site identified from orbit after the proposed MAX-C mission (although it is likely that a sufficiently compelling observation would lead to a change in the requirement).

9.2. Selection of a Landing Site of High Potential Interest

The site visited by a potential sample return mission should contain samples of high relevance to the life question, and a MAX-C site selection competition would provide an opportunity to evaluate candidates. Over the past 35 years, the Mars program has successfully visited six landing sites. However, three of those sites (Viking 1 and 2, and Pathfinder) are clearly not of broad enough interest to justify an astrobiology-focused MSR mission. The Phoenix site is likely not accessible to the potential sample return flight system and in any case would probably not be judged to be scientifically compelling from a “signs of life” viewpoint. Both of the MERs have encountered and documented past geological environments that are potentially habitable and thus hold interest for sample return. The two MERs are still operating and could yield new discoveries that might make one of their landing sites more enticing for sample return. Thus, two of six past sites are possible candidates for a potential astrobiology-focused sample return mission. However, with the recent improvement in our knowledge of Martian surface geology (notably from MRO), there is a consensus that from the perspective of potential sample return, more promising sites than these almost certainly exist.

FINDING: There are many candidate sites of high interest for a potential sample return beyond those previously visited or to be visited by MSL.

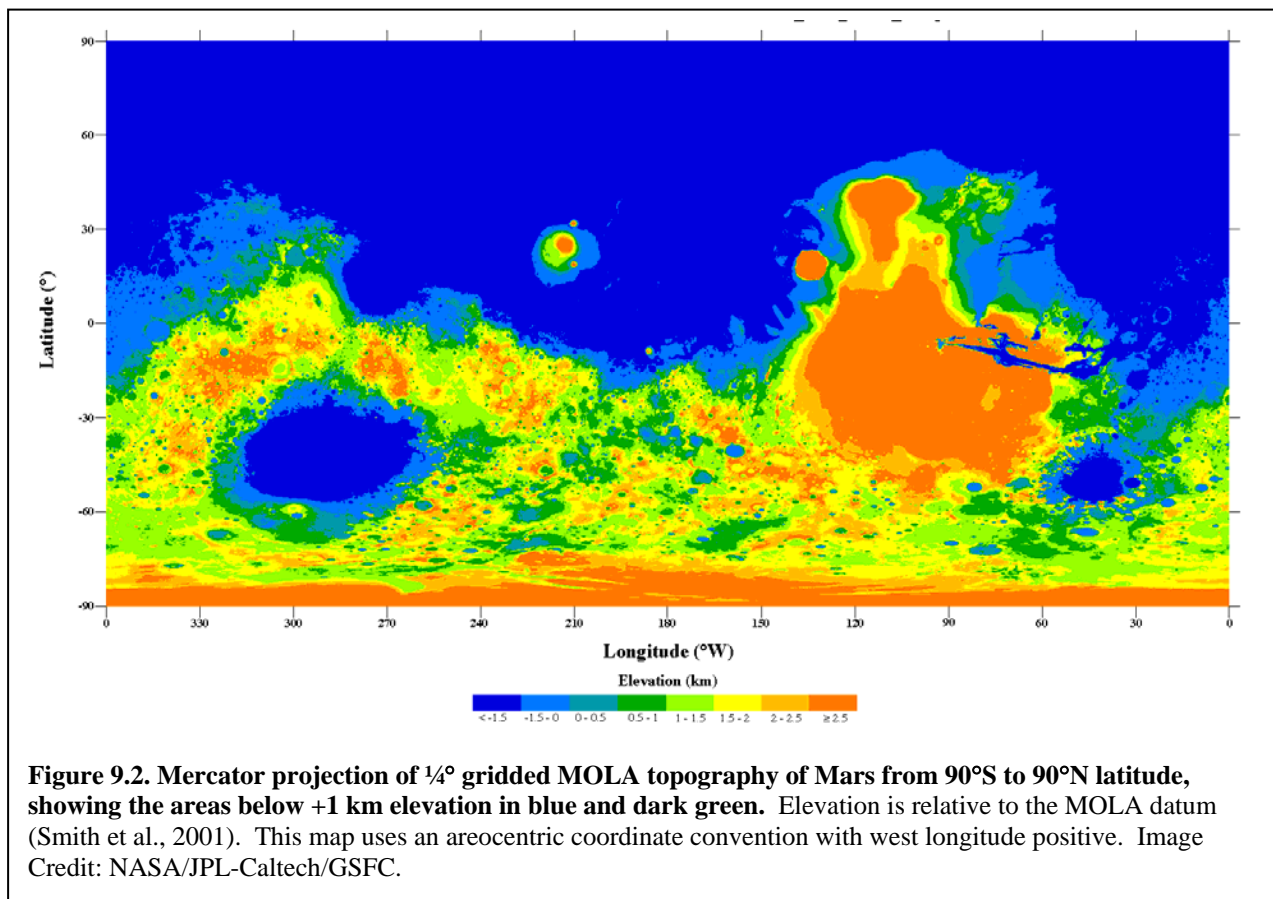
As our knowledge of the Martian surface has increased, there has been a parallel increase in the number and nature of sites having potential to contain outstanding samples for a possible sample return. In the area of astrobiology, the NRC (2007) recently listed some of the high-interest sites. In addition, at recent Mars-related conferences (e.g., LPSC, EPSC, AGU, 7th Int’l Conf. on Mars, EGU) the global Mars scientific community has developed multiple additional site-specific astrobiology hypotheses, the testing of which could substantially address the life question. The four candidate Mars Science Laboratory landing sites still under consideration as of this writing are also of interest from an astrobiology perspective. However, sample return scientific objectives go beyond astrobiology and habitability. For example, as recently discussed at the conference “Ground Truth from Mars: Science Payoff from a Sample Return Mission” (April 21–23, 2008, Albuquerque, New Mexico, <http://www.lpi.usra.edu/meetings/msr2008/>), other kinds of geological materials of interest include sulfate minerals (which may contain a record of Mars near-surface processes), igneous rocks (which are fundamental to understanding the martian interior), hydrous minerals (which may contain a record of fluid-atmospheric evolution and secondary alteration), a full spectrum of sedimentary rocks, samples that represent a depth profile, and others.

As with all landed missions to Mars, the best way to evaluate the multiple sample return landing site possibilities, priorities, and advocacy positions is through an open competitive landing site selection process. Developing a consensus for a potential sample return landing site would be essential for

generating a broad, politically valuable support base. The proposed MAX-C mission represents the first opportunity to hold an open, competitive selection process to identify a landing site with consideration of potential sample return criteria.

FINDING: The landing site selection process for a potential sample return mission should start as soon as possible to take full advantage of the currently orbiting high-resolution instruments.

It is extremely important that a broad spectrum of landing site possibilities be available for this landing site competition. Recent results from orbital missions, highlighted by those from MRO, indicate that many candidate landing sites for the proposed MAX-C mission will likely be located in the ancient terrains of the Southern Highlands, where the record of aqueous alteration and processes is best preserved and exposed. Experience with the MSL and previous landing site selection activities has shown that a range of candidate MAX-C sites should be available for exploration if elevations up to +1 km could be accessed, but restriction to progressively lower elevation would result in loss of a rapidly increasing number of attractive sites (see Figure 9.2).



FINDING: A significant number of candidate landing sites, of high relevance to the objectives of the proposed MAX-C mission, with elevations less than +1 km MOLA datum are known. It is very important for this proposed mission to preserve the option of accessing the Southern Highlands, for which this threshold is a practical minimum.

10. SOME ENGINEERING CONSIDERATIONS RELATED TO THE CONSENSUS MISSION VISION

10.1. Solar Power and Thermal Considerations

The proposed architecture would use solar arrays to power the rover. This would drive the power and thermal design and would result in a practical limit to latitude access for the mission. The desired mission duration of at least one Earth year (half a Mars year) and the season at landing would result in a requirement to be able to operate in nearly any seasonal extreme. In northern latitudes it would be winter at arrival and summer at the end of the mission. The opposite seasons are experienced for southern landing sites. Due to the eccentricity of the Martian orbit, northern latitudes are less severe on the power/thermal design than southern latitudes, allowing effective operation at sites as far north as 25°N and as far south as 15°S.

10.2. Entry, Descent, and Landing (EDL) and Rover Traverse Capabilities

The performance of the EDL system is an important player in defining the accessible landing sites on Mars, and in sizing some key rover attributes. The major EDL performance attributes relevant to this discussion are delivered mass, landing altitude, and landing ellipse size. In general, less mass can be delivered to a higher altitude, more mass to a lower altitude, but there are limits to this trade due to other engineering constraints (e.g., structural design, guidance and control considerations). The size of the landing ellipse is in part dependent upon EDL phase *a priori* attitude knowledge errors that propagate through the entry phase. The ellipse can be tightened up incrementally by tightening up the knowledge errors. Landing ellipse size is primarily of interest in order to improve access to specific features on Mars. Given that scientifically interesting features often represent terrain that is too dangerous to land on, the landing ellipse is often driven to be placed right up against but not on top of features of interest. The result is that access is often a product of both ellipse size and traverse capability sufficient to get outside of that ellipse in a reasonable amount of time relative to the mission lifetime.

The mass of the proposed MAX-C rover is estimated to be in a mass class much smaller than MSL, but larger than the MERs. This makes a reflight of the MSL Cruise/EDL system the prudent choice to deliver the proposed MAX-C rover to the surface of Mars. The proposed MAX-C mission would arrive at Mars in January of 2019 at an $L_s=325^\circ$ (northern mid-winter). Given the favorable atmospheric pressure at this time of the Martian year, performance of the MSL delivery system could possibly allow altitudes up to +1 km, depending upon the final landed mass. There are also unfavorable effects on the atmosphere from possible dust storms, and the combination of all of this has not been fully evaluated at this time. The landing ellipse size could be reduced from the MSL 10 km radius capability to as small as 7 km (Wolf and Ivanov, 2008). A traverse capability complementary to this would be provided to allow access outside of the landing ellipse.

In order to achieve the scientific objectives, it would be important for the rover to have a sufficient ability to apply its payload to particular features of interest (outcrops, layers, etc.). The proposed rover would have a mobility system physically similar to that of the MERs, only slightly larger. The traverse capabilities of the MERs are seen as the standard for such feature access. The key parameters behind a rover's ability to traverse slopes, sandy terrain, and rock fields are as follows:

- Ground Pressure: Defined as the ratio of the weight of the vehicle to the effective contact patch of its wheels. Ground pressure for the proposed MAX-C rover would be as good as or better than that of the MERs, allowing safe and effective traverse on loose or sandy slopes of as high as 10-12 degrees.

- **Static Stability Angle:** Defined as the complement of the angle from the ground up to the rover center of mass, measured from the various outer edges and pivot points of the rover suspension. The proposed MAX-C rover would be designed with a sufficiently high static stability angle to allow safe and effective traverse on well consolidated or rock-plated terrain up to ~30 degrees.
- **Wheel Size and Belly Clearance:** The diameter of the wheels and the distance from the belly of the rover to the ground defines the size of rock that is deemed an obstacle. The proposed MAX-C rover would be designed to be at least as large as the MERs in these parameters, allowing effective traverse in rock fields at least as dense as encountered by the MERs.

Another important capability for accessing features of interest is traverse rate (or effective daily average rate). In some landing sites it might be desired to traverse distances as far as 10 km to reach the features of interest. Given the modest lifetime of one Earth year suggested for the proposed MAX-C mission, the necessary traverse rate for the rover would need to be improved over past experience. It is estimated that a factor of 2 to 3 improvement over the actual MER capability could be required. Through the use of improved algorithms and hardware for navigation functions, it could be possible to increase the traverse rate for the proposed MAX-C rover by at least this much.

The MSL landing system (called “sky crane”) would likely be used for the proposed MAX-C mission and would result in similar engineering constraints on the landing ellipse (to first order) as those applied to MSL. By analogy with the MSL landing site selection process, many of the highest priority landing locations identified from orbit cannot be directly accessed and might require the ability to traverse beyond the perimeter of the landing ellipse. Although good scientific targets exist within all of the final candidate sites for MSL, primary scientific targets are near the edge or outside the ellipse for three of the final four candidate sites selected. Figure 10.1 shows an example of a “go to” type of landing site. Outcrop access would be essential to the scientific return of the MAX-C mission concept. Areas of extensive outcrop are typically associated with significant topography, which correlates to landing hazard for an MSL landing system. An alternative would be to land in a place where it is topographically rough but the landing ellipse contains all the targets of interest, and use hazard avoidance technology (Mourikis et al., 2009) during descent to land on a safe spot (see Figure 10.2 for an example of this kind of landing).

FINDING: The proposed MAX-C mission would require either (a) the ability to traverse beyond the landing ellipse to targets of interest or (b) hazard avoidance capability during EDL and an ability to traverse to targets of interest within the ellipse.

The use of hazard avoidance would reduce rover mobility requirements and would reduce the risk of a surface rendezvous with a potential sample return “fetch” rover. However, if hazard avoidance is not possible due to risk or cost reasons, an increased rover traverse capability could be relied on.

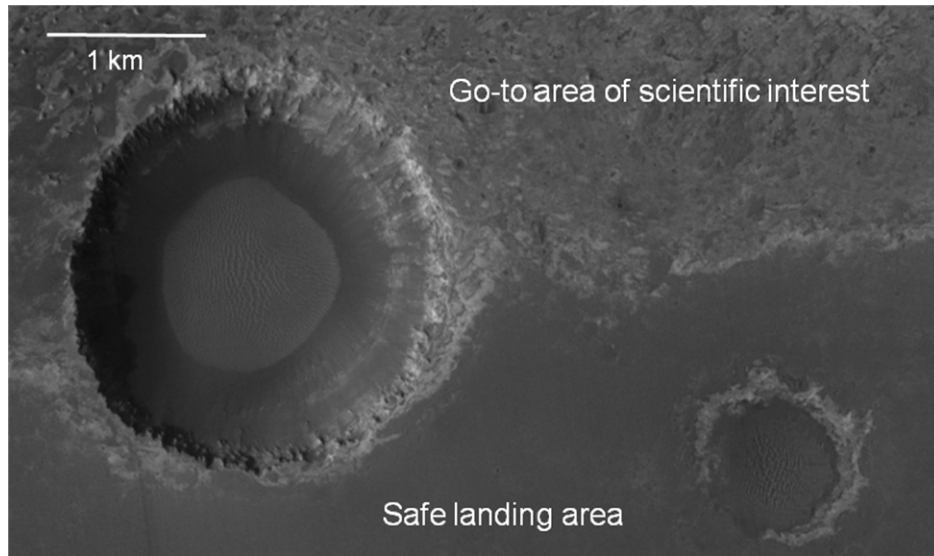


Figure 10.2. An example of a “go to” landing site that would be well suited for landing in the smooth safe area to the south but then requiring a possibly long rover drive to get to the area of scientific interest on rougher terrain. Mosaic of CTX images P05_003168_1825 and P06_003379_1827 shows a portion of a Northern Meridiani site that is no longer being considered for MSI. Image credit: NASA/JPL-Caltech/MSSS.

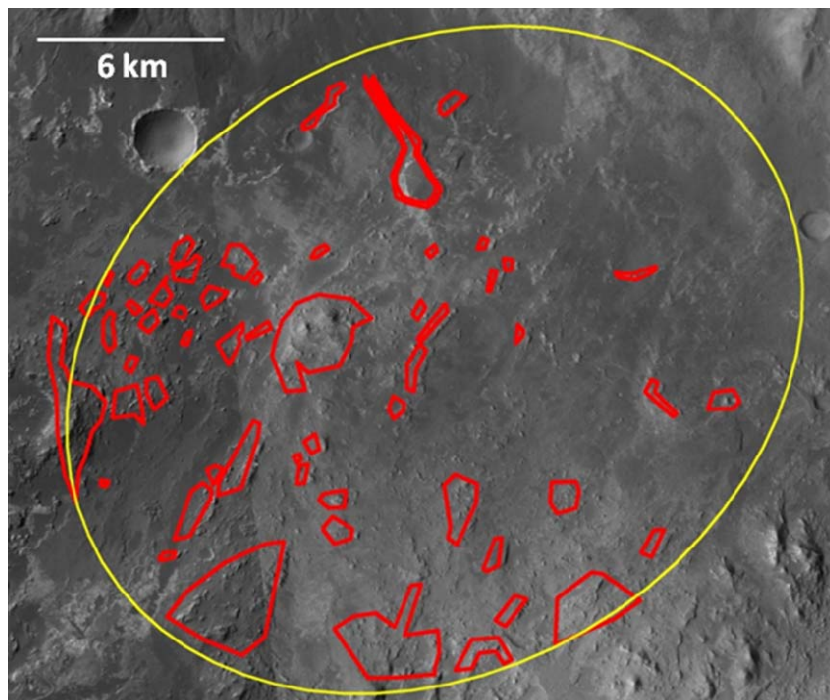


Figure 10.1. An example of a landing site that could benefit from hazard avoidance during descent, to avoid the rough terrain outlined by red polygons. Mosaic of CTX images P01_001336_1560 and P06_003222_1561, showing the ellipse for the Eberswalde candidate MSL landing site. Image credit: NASA/JPL-Caltech/MSSS, polygons generated by Eldar Noe Dobrea and Matthew Golombek.

Another kind of capability that would be extremely useful for the proposed MAX-C mission would be the capability to navigate on slopes of up to 30 degrees, as both of the MERs have done. Many of the geologically interesting terrains on Mars expose stratified layers on slopes in craters, channels, and hillsides. Access to these kinds of slopes would allow the proposed MAX-C mission to characterize a sequence of layers and lower the risk to achieving the scientific objectives. Limiting this capability could rule out certain landing sites, could cause a rover to take a much longer path to get to a target of interest, or could preclude access to certain targets of interest. Also, another consequence of limiting the slope capability is that it would increase the rover egress challenges for those architectures that include a landing pallet. Less slope capability means that smaller rocks become landing hazards. The ability to also acquire cores for the proposed cache while the rover is parked on a slope is also highly desirable, although this should be part of a future science/engineering trade study.

10.3. Sample Acquisition, Mechanical Handling, and Caching

10.3.1. Abrading

Abrading of surface material would be accomplished through the use of a specialized abrading bit placed in the coring tool (Zacny et al., 2008). The incremental mass and complexity of this approach, given the existence of the coring tool with bit change-out capability, is small (much smaller than adding a separate abrading tool). This tool would be intended to remove small amounts of surface material in order to allow instruments access past any dust and/or weathering layer. It would abrade a circular area of similar diameter to the core (8-10 mm). Translation of the arm would be used to scan or mosaic the individual abrasion spots to expose larger areas. Design parameters would be explored to strike a balance between the engineering desire to use percussion for efficient abrading and the scientific desire to have a smooth cut surface to observe. The surface contamination due to abrasion would need to be constrained to not to interfere with organic compound detection, if such an instrument is included in the payload.

10.3.2. Coring

Coring would be accomplished through the use of a coring tool on a 5-degree-of-freedom arm, to allow acquisition from a diverse set of targets. It could produce cores of approximately 10 mm diameter up to 50 mm long, which would be encapsulated in individual sleeves with pressed-in caps. The system would minimize mechanical handling of the cored material through a design that allows core acquisition to take place directly into the encapsulation sleeve. Bit change-out capability would also be provided to allow for bit wear, breakage, and loss of any kind.

Cores could be made available for observation through a mechanism to allow placing them on an observation tray at the front of the rover. In this tray, they would be accessible or visible by instruments on both the arm and mast. Cores placed in the tray could not later be encapsulated for placement in the cache. Once placed in the tray, and subsequent to any interrogations by mast or arm mounted instruments, cores would be discarded.

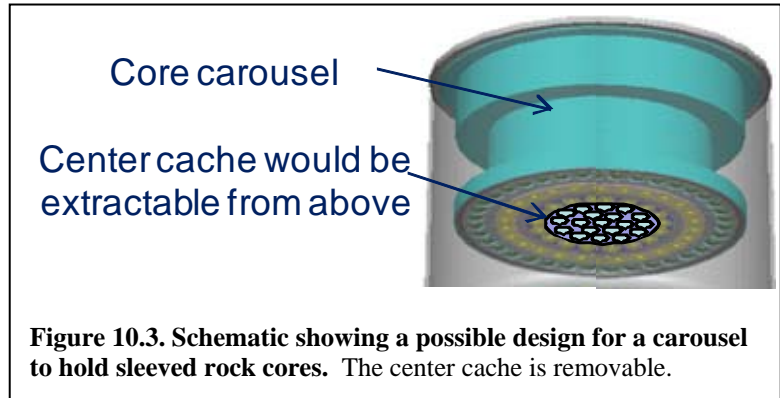
The nature of the coring tool would be rotary percussive (like a common hammer drill, see Stanley et al., 2007 for an example). It does not cut the rock, but rather fractures and pulverizes it in the impact patch (the circumference of the core). This percussive action results in minimal temperature rise of the actual core, especially across the multi-hour extraction process, but produces a slightly rougher surface than a pure cutting tool would.

10.3.3. Caching

The rover would be equipped with a mechanism for handling cores, capping their individual sleeves, and retaining them in a hexagonal packed cylinder (Figure 10.3 shows one example of how a cache could be configured. See Collins et al., 2009).

The coring bit (with sleeved core inside) would be released into the handling system as part of the transfer mechanism for each core. Bit change-out essentially would occur during transfer of every cached core, making it advantageous to combine the more general spare bit change-out function in the same system. The sleeved core would be retrieved from the bit, capped, and placed into the cache. Specification of the exact size of the cache would

be the subject of future trade-off studies, but it appears it would be feasible to incorporate a cache of 20-30 cores, plus some extra sleeves/caps to allow for swap-out and/or loss for whatever reason. The proposed MAX-C rover could be designed to place the cache on the surface of Mars at a location favorable for subsequent retrieval by a rover from a potential future mission, or to retain the cache for retrieval directly from the proposed MAX-C rover.



The entire core handling and caching assembly would be enclosed and sealed with the only entry point being a small port where the bit (with sleeved core inside) would be inserted for transfer. The bit port would be covered and oriented facing down so nothing could fall into it. This is all favorable for planetary protection and contamination control, which would impose rigorous requirements on this mission in order to produce a cache that would be valid for return to Earth (see Section 16, Appendix E).

The capability for the proposed MAX-C rover to drop off the sample cache at a location favorable for retrieval by a subsequent mission could make it much easier for a potential “fetch” rover to access quickly. Once the cache is dropped off, the proposed MAX-C rover could go into more rugged terrain for its own *in situ* science without increasing the risk to a potential sample return. This would benefit the analysis of potential returned samples by expanding the regional context of those collected samples.

10.4. Overall Risk and Cost Issues

The implementation described above would rely on significant inheritance of MSL cruise and EDL spacecraft designs to minimize cost and risk. Using an MSL design for cruise stage, entry body, and sky-crane landing system would be the proposed approach. This would result in substantive inheritance from MSL in the flight design, test design, and test and handling hardware. The intermediate scale of the proposed rover would drive a new mechanical and thermal development. The basis for the design would be well understood since it could draw upon the experience of MER and MSL. At the component level, the proposed rover would draw heavily upon MSL heritage. The result would represent a medium risk and medium cost for the rover.

A typical development schedule for this kind of project would be approximately 6 years, Phase A through D, plus some advanced technology development activities in the years preceding that. Based on this schedule and a full JPL Team X estimate, the MRR-SAG’s cost estimate is in the range of \$1.5-2.0B, real year dollars for a possible launch in 2018. The operations phase after launch plus 30 days is not included

in this estimate. The estimate does include a baseline Atlas V 531 launch service at an estimated cost of ~\$290M. Also included is ~\$70M in technology development activities to address the needs described in the next section, with the exception of instrument technology. It is assumed that key instrument technologies would be advanced as needed through other funding sources (i.e., MIDP or other such activity) to an appropriate readiness level to respond to an AO, from which point the remaining development cost would be provided by the project. For the entire estimate, cost reserves of 30% on top of the base estimate are also included.

10.5. Summary of Potential MAX-C Technology Development Needs

Several key technologies would need further development (Hayati et al., 2009) to support the mission concept. These include technologies in five areas:

- Coring, encapsulation, and caching: Lightweight tools/mechanisms would be needed to obtain and handle cored material.
- Instruments: Additional technology focus should be applied to instruments that could address the measurement needs posed herein, particularly the microscale mineralogy, organic compounds, and elemental composition mapping.
- Planetary protection/contamination control: Biocleaning, cataloguing of biocontaminants, and transport modeling to ensure cached samples would be returnable.
- Rover navigation: Onboard image processing and navigation to increase traverse rate.
- Entry, descent, and landing: Precision landing and hazard avoidance

10.6. A Programmatic Note

The proposed MAX-C mission concept has been studied by the MRR-SAG since April, 2009. The strategy has been to develop the most cost-effective concept to meet the *in situ* scientific and caching objectives. The resulting proposed rover would be in a mass class much smaller than MSL, but larger than MER. This makes an MSL Cruise/EDL system the prudent choice to deliver the proposed MAX-C rover to the surface of Mars. Recent high-level discussions between NASA and ESA have led to the possibility of delivering the ESA ExoMars rover and the proposed NASA MAX-C rover to Mars together in 2018 on a single launch vehicle with the MSL EDL system. This combined mission concept has been explored only briefly thus far. The implementation discussion in this report reflects a proposed NASA-only MAX-C mission, but the general capabilities for the proposed MAX-C mission would be expected to be similar for a dual mission architecture.

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12. APPENDIX A. MRR-SAG CHARTER AND PROCESS

12.1. Charter

Introduction

In the 2006 report of the MAPG planning team, a mission concept was formulated that was generically referred to as “mid-range rover.” This was originally envisioned as a mission that could be considered for flight in 2016 or 2018, in follow-up to the MSL and ExoMars rovers. In February, 2008, the MEPAG MSS-SAG (Murchie et al., 2008) discussed the possible purpose and value of a mid-range rover in more detail given our discoveries at Mars through 2007 and concluded that there could be three significant benefits:

- “Characterization of a new site follows up on discovery of diverse aqueous deposits
- Investigation of each type of deposit promises significant new insights into the history of water on Mars
- Provides additional context for proposed MSR samples”

The mid-range rover concept was then also included in the planning work of the MATT-2 team, which incorporated and extended the efforts of MSS-SAG. MATT-2 specifically endorsed what they referred to as the “Mid-Range Rover/Prospector” or “Mars Science Prospector” (and using the shorthand MPR) for the 2016 launch opportunity in both of their high-priority candidate architectures. They also provided some more detail (reprinted below) on the possible capabilities of MPR.

In light of recent discoveries and the MSL launch slip to 2011, the MATT-3 team recently updated the MATT-2 architecture analysis. Their assessment indicates that a mid-range rover should be considered for launch in 2018 or 2020.

It is now time to go beyond the above general concept description and analyze three things:

- the possible specific *in situ* scientific objectives that could be achieved by this mission
- the potential contribution to a potential future MSR that could be achieved by such a mission
- any long lead technologies that would enable or enhance the potential mid-range rover mission and subsequent potential MSR productivity

Assumptions

- The mission would include a single rover. Attributes: solar-powered, targeting accuracy of 3 km semi-major landing ellipse, rover range at least 5 km to enable exploration outside of the landing ellipse, lifetime > 1 Earth year, no requirement to visit a Planetary Protection Special Region.
- This would be a dual-purpose mission: 1) conduct high priority *in situ* science, 2) prepare for potential future MSR.
- The preliminary cost cap for the mission would be about \$1.3B (to be confirmed).

Requested Tasks

- (1) Evaluate the possible and probable discoveries from MSL and ExoMars that would feed forward to this mission.
- (2) Based on Task #1, the most recent version of the MEPAG Goals Document, and recent reports from the NRC, analyze the kinds of high-priority science that could be accomplished with this mission concept. Propose draft statements of scientific objective. Evaluate the kinds of instruments, kinds of

landing sites, and the nature of the surface operations needed to achieve candidate scientific objectives.

- (3) Determine the most important ways (scientific and/or technical) in which this mission could contribute to a potential future MSR.
- (4) Analyze the trade-offs associated with simultaneously optimizing Task #2 and Task #3.
- (5) Analyze the incremental value, which could come either from *in situ* science or potential MSR feed-forward or both, that could be achieved with a modest increase in budget over the baseline assumptions specified above.

Methods

- The SAG is asked to conduct its business primarily via telecons, e-mail, and/or web-based processes. One face-to-face meeting may be accommodated if needed.
- The Mars Program Office at JPL will provide logistical support.

Deliverables, Schedule

- The SAG is expected to begin its discussions in April, 2009.
- A midterm report in PowerPoint format by May 29, 2009.
- A draft white paper by the MEPAG meeting of July 28-29, 2009. The paper will be presented and discussed at that meeting.
- A final white paper report by September 1, 2009, incorporating comments raised at the MEPAG meeting, or other review processes.

Report Format

- The results of this SAG should be presented in the form of both a PowerPoint presentation and a text white paper. Additional supporting documents may be prepared as needed.
- The report should not contain any material that is proprietary or ITAR-sensitive.

Jack Mustard, MEPAG Chair

Michael Meyer, NASA Senior Scientist for Mars Exploration, NASA HQ

David Beaty, Mars Directorate Chief Scientist

Rich Zurek, Mars Program Chief Scientist

April 14, 2009

12.2. MRR-SAG Process

Weekly teleconferences of the MRR-SAG began April 14, 2009. Tasks (1) and (3) were delegated to MRR-SAG sub-teams. The analyses were reported back to the full group for discussion and establishment of consensus positions. Task (2) was worked by the full MRR-SAG team. A midterm report was presented to both the MEPAG Executive Committee and to MART on June 8-9, 2009. The MART recommended against planning to have a non-returnable sample cache that would only demonstrate coring, caching, and sample encapsulation. Their advice was that this mission should prepare a potentially returnable cache of samples. After consideration, the MRR-SAG agreed to follow this advice.

The MART feedback also resulted in the formation of two new sub-teams, one to focus on potential MRR mission objectives and measurements and the other to focus on the kinds of potential MSL, ExoMars, or MRR discoveries that would be sufficient to possibly trigger a sample return. The results of all these tasks were then integrated into a single high-priority mission concept with potential options in the trade between potential MRR *in situ* science and sample return feed-forward (Tasks 4 and 5). The MRR-SAG

presented their findings on July 29, 2009, at the MEPAG meeting in Providence, RI, and feedback from that forum was incorporated into the findings of this report.

13. APPENDIX B. MISSION CONCEPTS EVALUATED

This appendix provides a more detailed explanation of the 8 mission concepts considered in depth by the MRR-SAG, as well as comments on the 8 concepts by the MRR-SAG team members.

13.1. Mission Concept #1: Mid-latitude Shallow Ice

13.1.1. *In situ* Scientific Objectives and their Significance

This mission concept would investigate shallow subsurface ice deposits occurring at mid-latitudes whose presence have been inferred by recent orbital observations. Fundamental questions that could be addressed by this concept, and their linkages to MEPAG goals and objectives, include:

- *What is the habitability of mid-latitude ice? How does perchlorate affect the present day habitability of Mars?* (MEPAG Goal I A1:water; A3: CHNOPS; B1: organic carbon, B2: inorganic carbon-carbonate, B3: links between CHNOPS, B4: oxidation chemistry)
- *What are the characteristics of mid-latitude glaciers and their relationship to obliquity cycles?* (Goal II A1: processes controlling water; A2 interaction with surface materials; A3 investigation of microclimates)
- *Could mid-latitude ice provide a significant and accessible resource for human exploration?* (Goal IV.A1D)

These questions build on several recent compelling discoveries. For instance, although mid-latitude shallow ice (< 5 m depth) ought to be too unstable to persist on Mars today, it has recently been interpreted to exist based on observations of small impact craters by HiRISE/CRISM (Byrne et al., 2009a, 2009b) and also inferred separately based on observations of lobate debris apron features by SHARAD (Safaenili et al., 2009). Both of these features are found in the Phlegra Montes region. Lobate debris aprons, common in the mid-latitudes and long postulated to be ice rich (Lucchitta, 1984), are now known from ground-penetrating radar to consist mostly of ice (Plaut et al., 2009). Mars climate simulations suggest that significant distributions of mid-latitude glaciers could form rapidly during high obliquity (Forget et al., 2006). Mars glaciers could be as much as one million years old, an order of magnitude longer than any known glaciers on Earth, providing a means to investigate long term ice processes (Mahaney et al., 2007).

The Phoenix Mars Lander, a Scout mission to the northern high latitudes (68°N), has opened up a new path of investigation for Mars present day habitability with the partial characterization of an ice sublimation lag deposit, but stopped short of the confirmation of the presence of organic compounds. The occurrence of alkaline soils and perchlorate at the Phoenix site can both be favorable for habitability (Hecht et al., 2009), whereas the discovery of carbonate (Boynton et al., 2009) indicates formation in the presence of liquid water under alkaline conditions which could have been present as recently as the last obliquity cycle (Smith et al., 2009b). On Earth, signatures of biological activity have been found in profiles through glacier ice (e.g., Priscu et al., 1998). At northern mid-latitude sites with south facing attitude and low altitude, physical conditions needed for transient melting of naturally exposed ice might be met, providing habitable niches. Significant deposits of ice, if confirmed at mid-latitudes, could also be important and convenient as a resource for human exploration, as high latitudes and extended polar night make landing sites on the north polar cap ice reservoir unfavorable.

13.1.2. Investigation Strategy

The mission would focus on two *in situ* investigations, and target the landing ellipse on a recently formed crater in order to access a shallow ice profile through coring crater walls. The investigations would focus on:

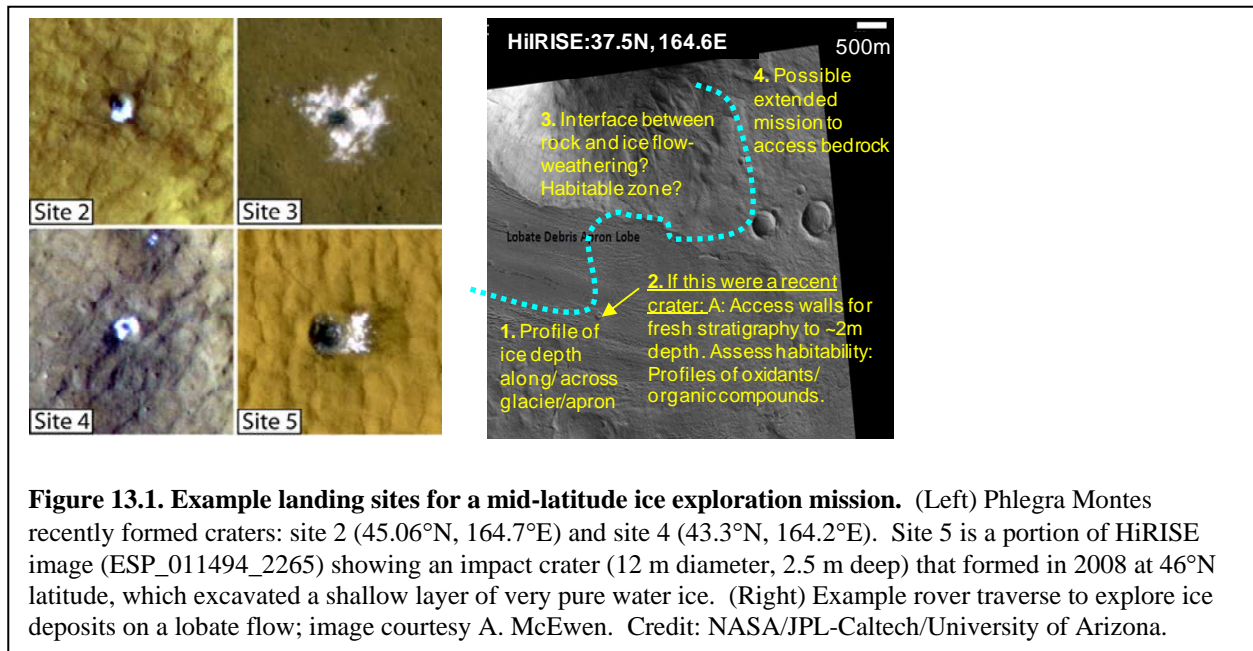
(1) Characterization of ice composition, including investigation of the depth distribution of salts, oxidants, and H/D, C, O, N, and Ar isotopes in order to determine the origin of the deposits and evaluate their habitability (e.g., Lacelle et al., 2008). The distribution of reduced carbon and organic compounds would also be investigated, with the observation method calibrated for the presence of perchlorate to build on Phoenix and Viking 2 analyses.

(2) Determination of the 3-D distribution of water via regional mapping on scales and depths relevant to calibration of the orbital sounding by MARSIS and SHARAD, and measurement of surface-atmosphere flux of water to understand current sublimation conditions.

The mission could be expanded to examine interesting geology at a scarp edge or weathering at the apron edge.

13.1.3. Landing Site Considerations

The ideal landing site would be a lobate debris apron with the landing ellipse centered on a recently formed crater in the northern hemisphere latitude band of 36-50°N and at altitudes of -2.5 to -4.5 km. Some examples of recent impacts into apparently water-rich deposits and prospective landing sites are provided in Figure 13.1.



13.1.4. *In situ* Mission Implementation

Nominal implementation would include a mast-mounted color imager to facilitate navigation to interesting sites. Ice sample acquisition would use a corer on a robot arm to access deposits in crater walls, with an elemental composition instrument to aid in sample selection and to support characterization of salts. Ice analysis would require an instrument package capable of analyzing isotopes, oxidants, and organic compounds, calibrated to ensure detection capability of organic compounds in the presence of perchlorate. Investigation of the distribution of subsurface water would use a shallow ground penetrating radar and an atmospheric package.

The exposed craters proposed as mission targets are small features on the order of meters in diameter, hence there would be a need for high landing accuracy. Mobility to reach an exposed crater would be key, providing access to a depth profile of ice through its crater walls. Feed-forward to a potential sample return mission would be demonstration of coring capability and investigation of a new type of mid-latitude site. Extension of the mission over a martian year would allow seasonal changes in water distribution to be monitored.

13.2. Mission Concept #2: Stratigraphic Sequence Near the Noachian-Hesperian Boundary

13.2.1. *In situ* Scientific Objectives and their Significance

The overall goal of this mission concept would be to understand the transition in surface conditions that occurred near the boundary of the Noachian and Hesperian epochs and to assess the geologic, biologic, and climatic implications of this transition. Many scientists believe that surface conditions on Mars changed dramatically near the end of the Noachian era. Erosion rates dropped 2-5 orders of magnitude (Golombek et al., 2006), valley networks with accompanying lakes are commonly observed in Noachian terrains but are rarely found in younger terrains (Carr, 2006), and primary Noachian igneous rock commonly underwent weathering to form secondary hydrous minerals such as phyllosilicates but might have rarely done so in later eras (Bibring et al., 2006). The observations are consistent with a change in surface conditions such that liquid water was much more readily able to participate in geologic processes during the Noachian epoch than in later periods. The transition occurred toward the end of the Noachian, although not necessarily precisely at the Noachian-Hesperian boundary as defined by numbers of superimposed impact craters, and is inferred to have occurred around 3.7-3.9 Gyr ago (Hartmann and Neukum, 2001).

The Noachian era is the one for which we have the best evidence for widespread habitable surface conditions as indicated by the abundant evidence of aqueous erosion, weathering, transport, and deposition. Arguably, therefore, this is the most likely era during which indigenous life could have arisen. The upper Noachian also coincides with the time when life might have started on Earth, and impact rates were still high, leading to the possibility that Mars could have been seeded from Earth (Gladman et al., 1996). However, it is not yet clear how persistent habitable conditions were during the Noachian, or whether they resulted from semi-permanent greenhouse warming or from episodic events such as large impacts (Segura et al., 2002) or volcanic eruptions (Baker, 2001) that produced temporary change of conditions. Whether habitable conditions were persistent or episodic would have substantial implications for life.

Accordingly, the objectives of this mission would be to: (1) evaluate surface conditions before and after the transition, and determine when and whether these conditions produced habitable environments, (2)

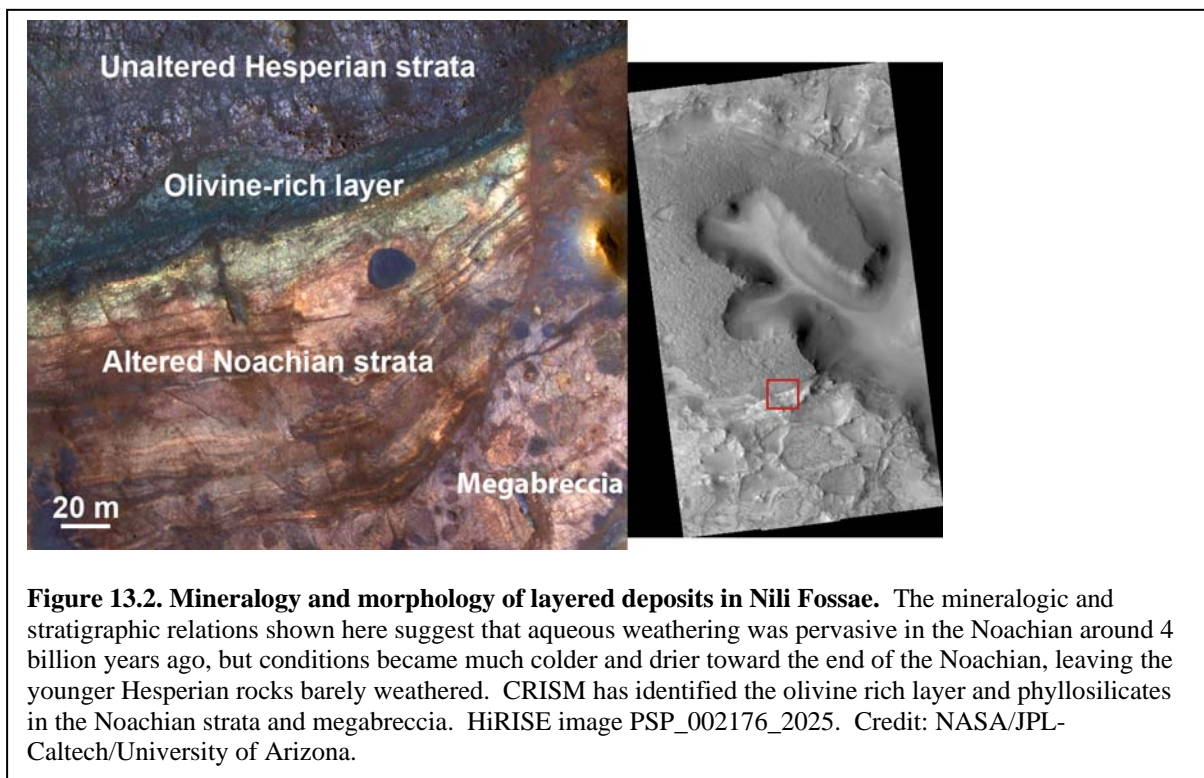
determine what environmental factors allowed the unique Noachian aqueous conditions, what caused the cessation of these conditions, and whether clement conditions were long lived or episodic, (3) investigate whether there is any evidence of life or prebiotic chemistry in rocks from this era, and, if evidence for life is found, to determine how it adapted to the changing environmental conditions at the end of the Noachian.

13.2.2. Investigation Strategy

The strategy would be to land close to a site where there is a continuous stratigraphic section in which Noachian rocks transition upward into younger rocks, and preferably where orbital data indicate that multiple Noachian units are present, each with a weathering profile. The proposed rover would then move up- or down-section, documenting the transition between altered older units and minimally altered younger units, and examining any weathering profiles that might be present. Clues as to the conditions under which weathering occurred would be obtained from measurements of the chemical, mineralogical and isotopic variations in the weathered units. The rocks would also be examined for the presence of chemical elements of particular biologic interest (C, N, S, P, etc.), organic compounds, isotopic signatures, and structures that might be indicative of life. Stratigraphic relations between the different weathered and unweathered units would be examined for clues as to the relations between incidence of weathering and terrain forming events such as impacts and volcanism. Of secondary importance would be determination of the age of the units involved.

13.2.3. Landing Site Considerations

The intent would be to land at a place where there is a continuous section from altered Noachian rocks upward through unaltered upper Noachian or Hesperian rocks. The section must be accessible for traversing by a rover. The preference is for a location where weathering profiles are in place rather than where alteration products have been transported and redeposited, as in a delta or an alluvial fan. The desired latitude range is 30°N to 30°S; the altitude range is -3 to +1.5 km. The concept depends on landing close to the section to be examined, which would likely be on sloping ground, so that the proposed rover might need to travel outside the landing ellipse. Of the final seven landing sites closely examined by the MSL landing site selection committee, the two that most likely contain a site that would fit this concept are Mawrth Vallis and Nili Fossae (example shown in Figure 13.2).



13.2.4. *In situ* Mission Implementation

The proposed rover would need a mast payload for remote determination of mineralogic and physical characteristics of surrounding rocks in order to select targets for *in situ* analysis. An arm would be required to acquire samples for analysis, and an abrasive tool or corer would be needed to get below weathering rinds. A sample processing system would be required to deliver samples to the analytical instruments. Desired measurements would be: (1) analysis of the chemical composition and mineralogy of rock forming components, including labile species such as bound water and halogens, (2) determination of the abundances and distribution of chemical elements of biologic interest such as C, N, S, and P, (3) determination of the nature of any compounds with reduced carbon, (4) analysis of the isotopes of key elements such as H, C, O, and N, and (5) some form of high resolution microscopy. Age determination, although desirable, would be a secondary goal.

13.3. Mission Concept #3: Radiometric Dating

13.3.1. *In situ* Scientific Objectives and their Significance

This mission concept would be to focus on radiometric dating of geologic deposits on Mars. Two basic mission types were considered in this concept. The first concept would acquire key radiometric ages for a particular site in order to improve calibration of the cratering record, which could then be used to date widespread terrains across the planet. The second concept would date a stratigraphic sequence of fundamental scientific importance in order to place it firmly in a historic context, analogous to the approach commonly used on Earth.

The cratering record of the lunar maria has been successfully calibrated to absolute ages via radiometric dating of returned lunar samples, and attempting this type of exercise on Mars has been proposed (Plescia and Swindle, 2007). Crater retention ages provide only a minimum estimate of the age of geologic units, but a tight minimum in the case of the lunar maria in which postemplacement modification has been almost entirely due to impact cratering. On Earth, subsequent processes erase craters to such a degree that crater retention ages are of no practical value. Mars is intermediate between the Moon and Earth in this regard, and the moderately active geology ensures a poorer result than that obtained on the lunar maria. However, we must rely on crater counts to quantify geologic time over the vast majority of Mars, and improved absolute constraints would certainly help constrain Mars' geologic history.

Radiometric dating has been one of the breakthrough technologies essential to understanding the history of the Earth. However, many thousands or millions of terrestrial rocks have been dated over widespread areas and with abundant supporting information, whereas a single Mars rover can only study the geologic units in a small area. Nevertheless, it could be useful to determine the absolute ages of a sequence of igneous and/or sedimentary rocks of fundamental scientific significance. For example, in concert with mission concept #4 (Early Noachian), absolute age constraints on possible biosignatures and the timing of paleomagnetism, differentiation, polar wander, and heavy bombardment would be very useful for establishing a timeline for the planet's early history. Radiometric chronology could also help evaluate stratigraphic models such as the concept of "mineral epochs" (e.g., Bibring et al., 2006). Dating could also determine the absolute age of a globally significant stratigraphic boundary, such as Noachian-Hesperian (e.g., concept #2) or Hesperian-Amazonian (or test hypotheses for the correspondence of these boundaries to actual bedrock units). Studies of polar or mid-latitude ice deposits (e.g., concepts #1 or #8) could also be aided by absolute ages. These questions are timely and of compelling significance because, in the absence of quantitative age information, we cannot truly understand the geologic, climatic and possible biologic history of Mars (we will be stuck doing "19th century" geology on Mars). Chronology is fundamental to understanding the history of Mars, with links to MEPAG scientific objectives IA2 (history of water), IB2 (inorganic carbon: distribution/composition), IB4 (preservation of reduced compounds), IIA3 (volatiles and dust surface/atmosphere exchange and effects on the distribution of surface/subsurface ice), IIB1 (stable isotopic, noble gas, and trace gas composition and evolution of the atmosphere), IIB2 (chronology, including absolute ages, of compositional variability), IIB3 (Relate low latitude terrain softening and periglacial features to past climate), IIC1 (rates of escape of key atmospheric species), IIC2 (physical and chemical records of past climates), IIC3 (evolution of stable isotopic, noble gas, and trace gas composition of the atmosphere), IIIA1-IIA10 (nature and evolution of the geologic processes that have created and modified the crust), IIIB2 (origin and history of the magnetic field), and IIIB3 (chemical and thermal evolution of the planet).

Either of the mission types considered could have scientific significance for a potential sample return. Age information would be essential to selection of the most informative samples to be returned. Quantitative geochronology could change perceptions of relative and absolute ages of units across Mars, changing scientific goals and targets for a potential return of samples. The mission might reveal information that suggests a potential sample return should or should not return to the same location. One possible shortcoming of this mission concept, however, would be that the best terrains for obtaining dates are in igneous rocks, and these rocks may not be optimal for containing signs of life.

13.3.2. Investigation Strategy

Essential information to be obtained for this mission concept would include: (1) radiometric ages of rocks or deposits determined to levels of precision required for particular scientific objectives; (2) sufficient geologic and petrologic context to assess the event to which the age refers; and (3) sufficient regional

geological context to constrain the age of associated stratigraphic records. Supporting information to be obtained would include residence time on the surface (cosmic ray exposure age) if a K-Ar system is used, geochemical constraints on magma source (initial $^{87}\text{Sr}/^{86}\text{Sr}$) if a Rb-Sr system is used, and information about petrology and chemical composition.

The geologic and petrologic characterization could be accomplished using a MER-like instrument package, while the radiometric dating would require a method-dependent sample handling strategy such as: (1) for Rb-Sr dating: sample externally measured in a RAT hole using an ion funnel (sample NOT placed in chamber) sample internally measured using a pencil-sized core (sample placed in a vacuum chamber), or (2) for K-Ar dating: sample powdered if necessary and placed on a transport system (sample placed in a vacuum chamber and transported/split out to XRF/LIBS, oven, and weigh station). Multiple rock analyses would be needed to reduce errors and uncertainties.

13.3.3. Landing Site Considerations

A landing site with a well-defined crater density and relatively unaltered volcanic rocks would be best to calibrate the cratering record. Landing site characteristics for a mission to date a stratigraphic sequence include: (1) presence of deposits of interest (Early Noachian rocks, major stratigraphic boundary, recent ice, etc.); and (2) a site that has suitably datable rocks (largely igneous, including large clasts in sedimentary deposits) with well-constrained cross-cutting or stratigraphic relationships. A 10-km landing ellipse and 10-km roving ability should be adequate for reaching a predetermined stratigraphic boundary, whereas a mission to calibrate the cratering record could accept a much larger landing ellipse. Candidate sites have been identified as part of other MAX-C mission concepts, or previous proposals to calibrate the cratering record (Plescia and Swindle, 2007). An example of a candidate suite for dating (but not the actual landing site) is shown in Figure 13.3.

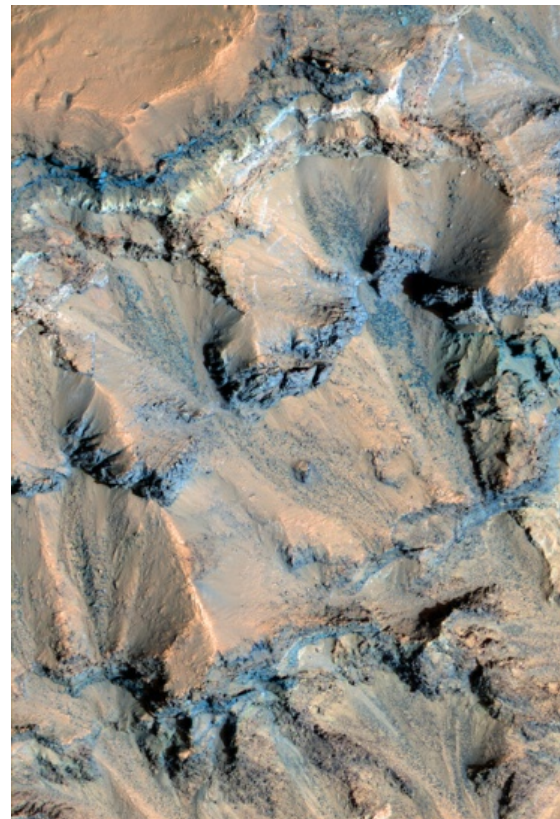


Figure 13.3. Example target site for a radiometric dating mission. Shown is a portion of a HiRISE color image showing interbedded unaltered lava (blueish enhanced colors) and deposits with hydrous alteration (light-toned units); steep slope in Asimov crater. From HiRISE image PSP_004091_1325. Credit: NASA/JPL-Caltech/University of Arizona.

13.3.4. *In situ* Mission Implementation

The equipment complement needed would consist of a MER-like or better instrument suite for geologic and petrologic characterization, and a geochronology system that would include a mass spectrometer. Also needed for K-Ar or Ar-Ar dating would be a means of heating and weighing samples and an analytical facility for determining elemental abundances (Swindle et al., 2003; Trieloff et al., 2009). Desorption and resonance lasers would be needed along with a mass spectrometer for Rb-Sr dating

(Anderson and Nowicki, 2009). Or, a luminescence instrument could be carried for dating very recent materials (Kalchgruber et al., 2007), e.g., for concepts #1 or #8.

Development of the necessary technology in time for a 2018 mission would be a major challenge for this concept (Conrad et al., 2009). The good news is that there has been substantial recent progress, and accurate *in situ* geochronology is within reach and appears to be a viable goal for future Mars exploration. There has been significant progress toward this goal from MSL instrument developments, particularly SAM for mass spectroscopy (Mahaffy, 2008) and ChemCam for laser-induced breakdown spectroscopy (Wiens et al., 2009). But, key new technology developments would be needed for accurate *in situ* experiments. The K-Ar system would require a means of heating samples to ~1600°C and weighing samples accurately, as well as a demonstration of sample acquisition and measurement by an end-to-end system. The Rb-Sr system would require the development of small resonance lasers. Also, the sample acquisition and handling system needs to be better defined for both approaches. For both systems, the mass (~25-30 kg) and cost are poorly defined but would probably exceed nominal expectations for the 2018 opportunity.

13.4. Mission Concept #4: Astrobiology Mission to Early Noachian Mars

13.4.1. *In situ* Scientific objectives and their Significance

The overall objective of this mission concept is to interpret environmental conditions at the surface during the earliest period of martian history, and to investigate the implications of these conditions for the potential origin and evolution of life on Mars. A particular version of this concept (rover exploration of a Noachian-age crater to provide a ‘window’ to the past), has been advocated in a Decadal Survey white paper by Schwenzer et al. (2009). Investigation of Early Noachian terrains would provide fundamental information regarding the habitability of Mars and the other terrestrial planets (Westall, 2005; Westall et al., 2008) at a critical period in early solar system history when life may have first appeared. Study of early Mars is particularly critical in this context because the ancient crustal rocks that could have contained traces of this “prebiotic” period on Earth have been completely recycled by plate tectonics, weathering, and impacts. Study of rocks from this epoch would provide information on the early differentiation and formation of the crust, the occurrence and distribution of water, the composition of the atmosphere, the history of the magnetic field, and the composition of the initial inventory of organic compounds. If life ever arose on Mars, the Early Noachian terrains might contain traces of that life, or of the transition from a prebiotic world to a planet colonized by primitive cellular life forms, as well as the early evolution of cellular structures. Finally, early crustal rocks record the changing environmental conditions that resulted from the demise of the planetary magnetic dynamo, loss of atmospheric volatiles, and impact flux during the late heavy bombardment, and might also record the effects of these environmental changes on the distribution of life. Even the proposed investigations produce a convincing negative result with regard to life (i.e., evidence that life was not present in the early Noachian rocks), this result would be very important because it would lead us to reevaluate our concepts of what constitutes a habitable planet and of the conditions that allowed life to originate on Earth.

As conceived, the main objectives of the mission concept would be to:

- (1) study the composition and origin of Early Noachian crustal materials in order to understand early terrestrial planetary evolution and the origin and composition of the crust,
- (2) study the prebiotic environmental context (climate, elemental ingredients, energy, magnetic field, etc.) in which life potentially arose, or the environmental context of any potential transitions from a prebiotic world to primitive cells,

- (3) evaluate the habitability of early Mars and how habitable conditions evolved with time; determine the distribution of liquid water, prebiotic organic compounds and life-essential elements (C, H, N, O, P, S, plus certain metals), and energy sources,
- (4) search for indications of primitive microbial life and/or prebiotic processes and materials in the rock record (i.e. nonbiological organic compounds), while recognizing that it will likely require a potential sample return to definitively identify such traces,
- (5) detect remanent magnetism *in situ* to determine the nature and paragenesis of magnetized mineral phases and lithologies and thereby constrain the nature and history of the martian dynamo, and
- (6) study the attributes and fate of any life as conditions on Mars changed relative to the history of the magnetic field, atmospheric loss, impact cratering rate, etc.).

13.4.2. Investigation Strategy

The suite of rocks to be studied should provide information on:

- the nature of the crust and early surface environment;
- the nature, timing, and distribution of aqueous activity on early Mars, especially evidence for interaction of water with rocks on timescales of 10^5 to $>10^6$ years (i.e., sufficient time for the origin of life);
- the composition, isotopic signature, and distribution of organic carbon with respect to different types of environment;
- signatures of primitive cellular life (e.g., carbon molecules and their chirality, isotopic signatures, morphological fossils) and its distribution with respect to different types of environments (e.g., standing bodies of water, hydrothermal activity, and habitats in rock pores (endolithic environments) or within cracks in rocks (chasmolithic environments));
- nature and distribution of remanent magnetization and its evolution in time; and
- composition of the atmosphere and its evolution in time.

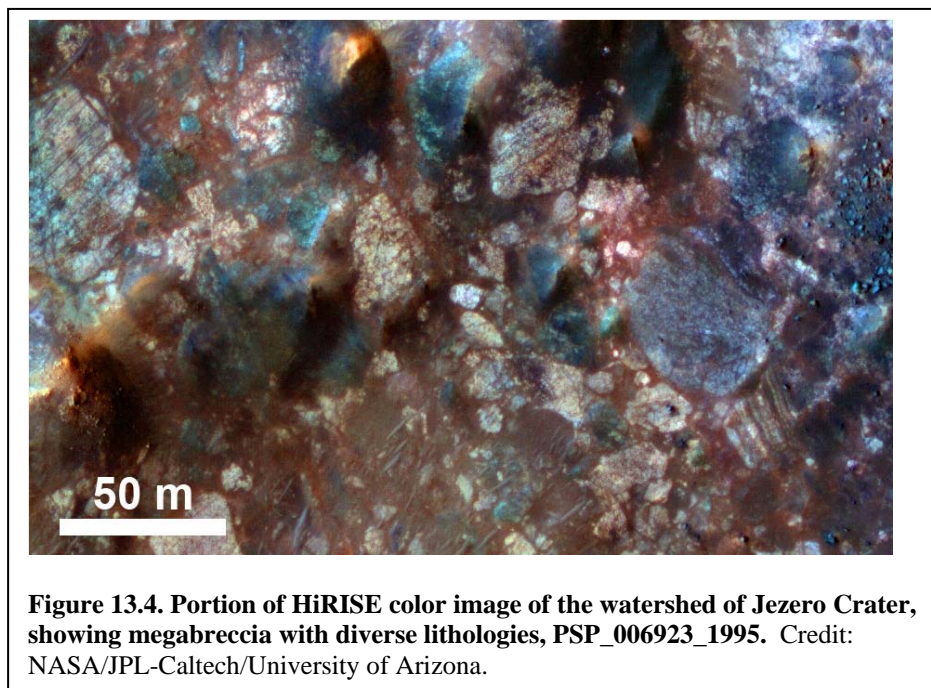
Definition of an exploration strategy for an Early Noachian mission presents significant challenges since access to these terrains could be problematic because the early crust may be largely buried and heavily brecciated (Grant et al., 2008; McEwen et al., 2009). The objectives to evaluate the geological history and evolution of habitability of the surface of the planet, as well as to seek evidence of the possible appearance of life, would necessitate access to rocks of different ages and different types. The ideal site would have a stratigraphic section containing sedimentary rocks for addressing the habitability/life objectives (Westall et al., 2008) and igneous rocks for assessing the magnetic field history (and for age dating). Megabreccia could provide an alternative means of accessing the range of materials and ages necessary (see Lindgren et al., 2009), although with a greatly reduced ability to interpret geologic context and interrelationships.

13.4.3. Landing Site Considerations

Noachian terrain landing sites (with a 10 km ellipse) could be found within the elevation range of -3 to +2 km. Ideal landing sites would include layered Noachian sediments, as well as volcanic rocks. Additional site selection criteria could include, for example, presence of phyllosilicates (as an indicator of aqueous deposition) and megabreccia (as a means of accessing diverse lithologies).

Some megabreccia sites (e.g., Holden crater) and associated overlying younger strata would provide the opportunity to access sedimentary rocks with clear bedding relationships ranging from Noachian to early Hesperian in age (Grant et al., 2008). Others, like the watershed of Jezero crater, would provide access to exposures of megabreccia with diverse rock types (Figure 13.4). Nili Fossae might provide access to

some of the oldest bedded lava sequences on Mars (Mustard et al., 2008). The northern rim region of Hellas basin might be promising for exposures of both layered and brecciated Early Noachian bedrock (McEwen et al., 2009).



Numerous outcrops of phyllosilicates in the Noachian highlands occur in outcrops, crater walls, rims, ejecta, and central peaks and in the walls of depressions and Valles Marineris (Poulet et al., 2005; Murchie et al., 2009). A variety of phyllosilicate mineral groups is indicated by spectral signatures, with Fe/Mg-clays being the most common minerals. The phyllosilicate-bearing outcrops are overlain by younger Noachian and Hesperian plains units, and are interpreted to represent the very old crust.

13.4.4. *In situ* Mission Implementation

The necessary ground operations for such a mission would include obtaining contextual observational information at all scales down to 12-15 μm resolution, as well as mineralogical and elemental composition of the materials to identify their nature and mode of formation to make conclusions regarding environmental conditions during their formation and evaluate their habitability, determine the presence of organic carbon in the rocks, and make magnetic measurements. The contextual measurements should be made on outcrop surfaces as well as on drill cores.

Equipment requirements would include:

- Rover capable of getting out of the ellipse and traveling an extra two or more kilometers beyond.
- Deployable instrument arm, mast camera, corer, surface abrader, color macro/microscopic imaging of rough and cleaned rock surfaces, mineralogical/elemental analysis of rock surface/core; organic carbon detection in the rock surface/core; chemical/isotopic/chiral analysis of the organic carbon; and magnetometer. Radiometric dating would be strongly favored for an augmented mission.

An early Noachian mission would be directly relevant to a potential sample return, in that the mission would have a significant potential to identify a site containing rocks that could address the main question “Did life ever appear on Mars?” and would provide fundamental information about the early terrestrial planets and their potential habitability. Materials could be also cached as part of this mission. However, a caching capability would negatively affect the weight constraints for the detailed characterization of the rocks and it would be difficult to decide which sample to cache without a preliminary area survey.

13.5. Mission Concept #5: Astrobiology: New Terrain

13.5.1. *In situ* Scientific Objectives and their Significance

The overall objective of this mission concept would be to investigate a novel site with a potential to support life in order to expand the diversity of astrobiology-relevant sites characterized *in situ* by landed missions. This concept would visit a site in previously unvisited ancient terrain which would allow us to:

- explore an astrobiology-relevant site that is very promising and qualitatively distinct from previously visited sites, and thereby expand our knowledge of the range of habitable environments on the planet,
- capitalize on new discoveries of sites of astrobiological interest on Mars as well as improved information on the diversity of life and the nature of biosignatures based on terrestrial studies,
- characterize geologic and climatologic contexts of the composition, landscape and aqueous processes at the site,
- test life-related hypotheses related to an additional type of geologic terrain or geomorphic feature (many good examples have been proposed), and
- determine whether habitable environments existed in the subsurface or surface for a sustained period of time at the site.

This proposed mission would address several MEPAG Objectives, including: 1A – Assess the past and present habitability of Mars; 1C – Assess whether life is or was present on Mars; 2A – Characterize Mars’ atmosphere, present climate, and climate processes; 3A – Determine the nature and evolution of the geologic processes that have created and modified the martian crust; and 4A – Obtain knowledge of Mars sufficient to design and implement a human mission with acceptable cost, risk and performance.

Primary mission objectives at the landing site would be to determine whether the landing site demonstrates clear evidence of past or present habitability, and whether the site contains material that can preserve evidence of past or present life. The rover would demonstrate whether that material could be collected and analyzed, and whether that material could be transported to Earth by a subsequent potential sample return mission. In support of this effort, the rover would be designed to document the site’s geologic context, current environment, and suitability for potential sample return.

13.5.2. Investigation Strategy

The operations strategy for acquiring the needed information would start with site selection – finding a site that was a past or present habitable environment and that could be accessible to a potential sample return spacecraft. The rover would explore its landing area to establish geologic context for the samples. It would locate optimal sites for sampling and analysis, and collect samples with mineralogy that is likely to preserve evidence of past or present life. The rover would analyze these samples for evidence of life. The chain of site selection, sample collection, and analysis demonstrated by this mission would determine the suitability of this specific site and materials for a potential sample return mission.

13.5.3. Landing Site Considerations

The concept – geologic terrane of potential significance to astrobiology or hydrology that has not yet been visited, where a specific astrobiology hypothesis could be tested – encompasses a wide range of potential landing sites. Many examples worthy of consideration have already been identified, and include: Noachian craters containing acid-saline lake and/or clay-rich deposits, evaporite sites containing chlorides or carbonates (example shown in Figure 13.5), mud diapirs that expose minimally-altered samples from depth, and gullies that show evidence of recent water flow. It is also anticipated that continued orbital observations and analysis of orbital data from OMEGA, CRISM, and HiRISE will result in many additional potential sites. Many of these sites are within the latitude and altitude constraints currently being considered for both the proposed MAX-C mission and potential sample return missions. The combination of precision landing and roving outside of the landing ellipse would be essential to the goals of this mission design, to fully characterize the site and access optimal sampling targets.

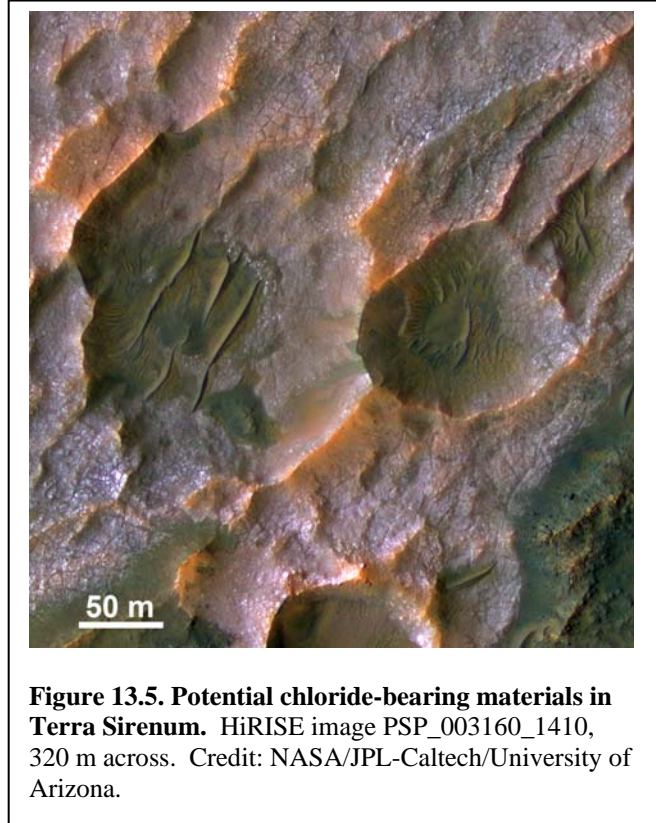


Figure 13.5. Potential chloride-bearing materials in Terra Sirenum. HiRISE image PSP_003160_1410, 320 m across. Credit: NASA/JPL-Caltech/University of Arizona.

13.5.4. *In situ* Mission Implementation

Mission capabilities that would be required to accomplish the objectives include the abilities to characterize the landing site's geologic context, to select and acquire the optimal geologic and atmospheric samples, and to conduct geologic and organic analysis of rock samples. The straw-man mission design would be an enhanced version of the MERs, and would include many capabilities currently operating on these vehicles including: a mast, color stereo imaging, remote mineral identification, an arm, close-up imaging, elemental determination, mineralogical determination, and the ability to remove weathered or dust-coated surfaces. In addition, the mission concept would call for the capabilities to drill rock cores, scoop regolith, sample the atmosphere, conduct microscopic multispectral imaging, and identify organic volatiles and associated biologically important constituents in rock, soil, and atmosphere samples. The mission concept would call for collecting and analyzing 20 rock cores in 4 suites, 4 soil samples, and 20 atmosphere samples.

This mission concept would include a requirement for surface operations spanning at least one martian year. This is based on MER experience of the time needed to assess the geologic context, the potential sample return feed-forward desire to record the full annual range of surface conditions, and the desire to monitor seasonal variations in atmospheric trace gas abundances. The mission concept would include a demonstration of precision landing and rover range sufficient to leave the landing ellipse. This combination is considered vital for a potential sample return mission, considerably expanding site selection possibilities, and allowing site selection to be more coupled to science and less coupled to EDL

parameters than on previous missions. Finally, the mission concept would include cleaning and sterilizing rover sampling hardware to the planetary protection standards that would be required for a potential sample return mission.

This mission concept would be amenable to sample caching. However, a cache would be neither required nor recommended. The mass, power, and volume requirements for sample caching would either lead to a significantly larger rover than currently envisioned, or seriously degrade the rover's capabilities for site characterization and sample analysis. This mission concept would demonstrate site-specific sample acquisition, which must be done on Mars prior to a potential sample return. However the next step – actual encapsulation of the acquired samples – could be adequately demonstrated on Earth.

This mission concept would be specifically designed as a precursor to a potential sample return mission. The landing site for the concept mission would be selected as a prime candidate for eventual sample return. The site would be evaluated for compatibility with the profile of a potential sample return mission. Site-specific planetary protection characteristics would be demonstrated. Optimal sampling locations for MSR would be identified. Optimal sample types for MSR would be demonstrated by *in situ* analysis. A set of rock, soil, and atmosphere sample selection and acquisition techniques relevant to MSR – and meeting MSR planetary protection requirements – would be demonstrated.

In addition, this mission concept would include *in situ* analysis for evidence of past or present life in the rocks, soil and atmosphere. These results – on their own – could significantly advance our understanding of astrobiology on Mars.

13.6. Mission Concept #6: Deep Drilling

13.6.1. *In situ* Scientific Objectives and their Significance

The overall objective of this mission concept would be to utilize drilling to access subsurface samples that could provide information not available from surface analyses, such as the origin and distribution of oxidants and geologic/geochemical history of sedimentary deposits. Geological analysis often requires investigation of vertical processes extending into the subsurface and reconstruction of 3-D geometries of geological features. In a flat and relatively structureless environment (i.e., one lacking outcrops exposing stratigraphic layers), drilling could be the only means to obtain data for the vertical dimension. Even in areas with outcrops, drilling could provide data to be correlated with outcrop surveys, unaltered samples, and uncontaminated samples.

One of the main issues that could be addressed by drilling is the extent of the superficial oxidation layer. Moreover, we are not sure whether the oxidation fronts move downward from the surface or upward from the subsurface. The nature of the oxidation could be investigated in detail with a set of samples showing trends of weathering with depth. All these data could contribute in understanding the causes of oxidation and the details of this process. The same approach could be used for meteoritic carbon; the kinds of processes affecting its cycle are unknown. These two aspects could be related also with the entire set of processes linked to the interaction between the atmosphere, the planetary interface, and the uppermost subsurface.

Direct data from the subsurface would help also in understanding the geological history of sediments and the paleoclimatic changes that are usually preserved in sediments and regolith. The drilling would be able to operate on consolidated rocks and on unconsolidated sediments. This flexibility would allow this technique to analyze ancient and modern sedimentary environments. Drilling could provide clues about

the nature of environments and morphologies that are observed only as superficial expression, such as lake floors, interior layered deposits, gully deposits, or delta deposits.

13.6.2. Investigation Strategy

A 1-to-2 meter deep drilling investigation would bring data from an hitherto neglected environment that might be unaltered and be the interface for a number of processes (Kminek and Bada, 2006; Pavlov et al, 2002; Parnell et al., 2007). Drilling would provide access to consolidated rocks that could not be analyzed in outcrops, for example lakebeds, outcrops in steep cliffs, and bedrock covered by thin eolian deposits or regolith.

The collection of data could be performed in three ways:

- collection and analysis of material recovered from the bore hole,
- data collected by instruments deployed inside the drilling tool through a window, and
- data collected by instruments deployed inside the borehole (standard borehole approach used on Earth)

The first method is the one present on the drill planned for ExoMars (Figure 13.6). Samples would be collected from the bit at a selected interval, recovered to the surface, and deployed on a platform in contact with analytical instruments. The second method requires a large energy budget and the capability to handle heavy and large cores. Within the framework of the current missions it seems quite unlikely that it would be possible to operate such a kind of system. The third system would involve deployment of instruments within the borehole. This could be done after the drilling if the walls do not collapse or, like on ExoMars, directly from the drilling pipe.

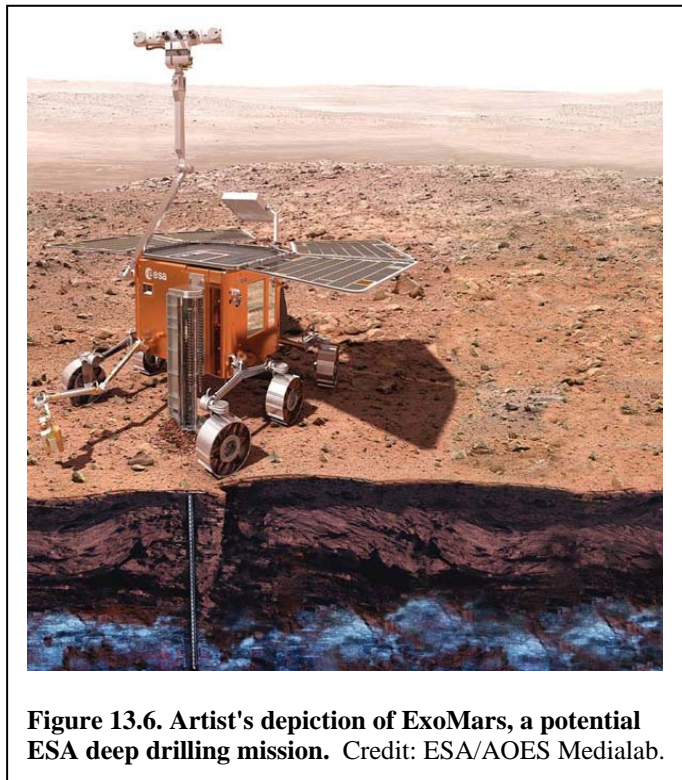


Figure 13.6. Artist's depiction of ExoMars, a potential ESA deep drilling mission. Credit: ESA/AOES Medialab.

The drilling itself could be performed in a few different modes:

- a rotary drill with the capability to collect samples scattered throughout the borehole has been implemented for ExoMars.
- a prototype ultrasonic drill has been tested with good results: cores and borehole walls were very clean, walls did not collapse, and the drill was able to cut rocks as hard as basalts.
- a continuous core drill bears a number of problems such as overwhelming mass, large energy budget, and difficult core handling

The two first methods have been tested in several instances and their efficiency has been proven. Although the rotary drilling with scattered cores has been implemented for ExoMars, the ultrasonic drill has undergone a large number of tests and has demonstrated good performance on very hard rocks.

13.6.3. Landing Site Considerations

A mission carrying drilling equipment could be useful in several landing site contexts. In a flat area without evident geological structures, drilling could provide data otherwise unreachable, whereas in an area with outcrops it might provide unaltered and uncontaminated samples of nearby outcrops or provide data to correlate with different and distant exposures. The examples belonging to the first case include lake beds, sedimentary basin floors and margins, and evaporitic and clay deposits. Iron-rich soils or surfaces could also be good targets.

Hydrothermal sites, mud volcanoes, spring deposits, and any other areas where subsurface fluids and gases may have reached the surface must be investigated by drilling in order to understand the processes and nature of degassing events. However, any area where scientific targets could be reached only in the shallow subsurface are landing sites that could be considered for a deep drilling: shallow ice in gullies or other mid-latitude glacially-influenced deposits, shallow ice in periglacial areas, and purported gas hydrates in the shallow subsurface.

13.6.4. *In situ* Mission Implementation

The equipment needed for drilling the martian subsurface has been investigated for the ExoMars drill. This drill would be based on the mechanical approach with a rotary system. However, its implementation would be similar to the one for the ultrasonic drill. The drill could be mounted on either a lander or rover. On a lander, it is of course a better sampling tool than a scoop or other sampling system, which are not able to investigate below a few centimeters. Wherever you land, the drill would be able to provide a set of samples that would probably be unaltered and pristine. On a rover, the drill would provide vertical mobility in addition to the horizontal mobility and it would be capable of revealing detailed facies changes and reconstructing 3-D stratigraphic patterns.

The drilling system would consist of a few assemblages:

- A deep drill composed of several pipes (rods) to reach 1-2 meters of depth
- A deployable structure to put the drill rig in contact with the surface
- Tools to deliver the samples into the analytical instrument(s) and into the cache

13.7. Mission Concept #7: Methane Emission from the Subsurface of Mars

13.7.1. *In situ* Scientific Objectives and their Significance

The overall objective of this mission concept would be to investigate the source of methane discharges to the martian atmosphere and to evaluate whether the methane has a biological or nonbiological origin. Recent reports of methane in the atmosphere of Mars (Formisano et al., 2004; Krasnopolsky et al., 2004; Krasnopolsky, 2007; Mumma et al., 2009) have reinvigorated the debate concerning the possibility of martian life. Of particular interest is the conclusion of Mumma et al. (2009) that mappable plumes of atmospheric methane were present in summer 2003 over a region in the northern hemisphere that includes deeply fractured Noachian crust in Nilli Fossae and adjacent volcanic debris from Syrtis Major (Figure 13.7). Given the strongly oxidizing composition of the atmosphere and dynamic photochemistry on Mars, the lifetime of methane molecules is likely to be less than a few hundred years, and active release of methane from the subsurface is needed to sustain atmospheric anomalies (Atreya et al., 2007; Geminale et al., 2008). Current data from Earth-based telescopes and instruments orbiting Mars are insufficient to determine whether methane release occurs at discrete vents or disseminated over broad regions and no consensus has emerged on the most likely mechanism for formation, because reduction of

carbon atoms to methane is a plausible geochemical reaction in magmatic processes, during aqueous alteration of mafic or ultramafic rocks (e.g., Oze and Sharma, 2005), in methanogenic microbial ecosystems based on hydrogen consumption, or in fermentation and during thermal alteration of buried organic matter. Whether the ultimate origin of methane is determined to be biotic or abiotic, the presence of methane has profound implications for astrobiology because methane and related volatiles might provide a source of energy for life (Allen et al., 2006). Regardless of the origin, methane emission from the martian subsurface could be recorded by alteration of oxidized surface materials and/or by formation of distinctive suites of minerals containing partially to fully reduced metals such as iron and manganese. Detection of ferrous/ferric phyllosilicates such as chamosite on Mars (Poulet et al., 2005; Bibring et al., 2006; Mustard et al., 2008) is particularly significant as an indication that partially reduced geochemical signatures at sites of alteration can be preserved despite exposure to the martian atmosphere.

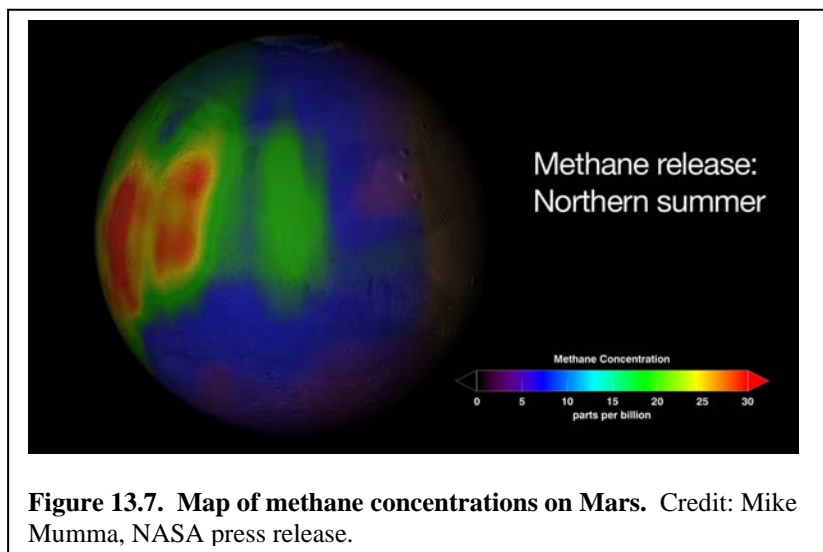


Figure 13.7. Map of methane concentrations on Mars. Credit: Mike Mumma, NASA press release.

The extent to which methanogenic or methanotropic microbial processes could be involved in a cryosphere methane cycle on Mars is of compelling scientific and philosophical interest, drawing attention to the fact that little is known about sequestration and emission of microbial CH_4 from regions dominated by permafrost, ground ice, ice sheets and altered crystalline rock on Earth (Mastepanov et al., 2008). Given the lack of structural variation for the symmetrical methane molecule, the stable isotopic composition of hydrogen and carbon atoms is often used to infer abiotic versus biological formation of methane on Earth (Whiticar, 1999; McCollom and Seewald, 2001; Sherwood Lollar et al., 2008) and, by analogy, on Mars (Onstott et al., 2006). The potential for overlapping source signatures however suggests that such isotopic measurements are most effective when coupled with compositional and/or isotopic analysis of associated gases, such as ethane, propane, and higher hydrocarbons (Sherwood Lollar et al., 2006). Terrestrial analog studies suggest that H_2 is present at moderate to high concentrations when associated with methane from geologic sources (volcanic gases or serpentinization) but is below detection or at trace-level concentrations when associated with methane of biologic origin (microbial or thermogenic alteration of buried organic matter). Determination of the CH_4/H_2 ratios for martian emanations could be a critical parameter for interpretation of source (Sherwood Lollar et al., 2007).

13.7.2. Investigation Strategy

The proposed mission would far exceed the capability of MSL for determining the origin and source of methane, by having instruments capable of determining the concentration and isotopic composition of

atmospheric methane and H₂ hydrogen as well as the relative concentration of hydrocarbons heavier than methane. Landing site selection would depend on refinement of spatial and temporal patterns of methane and H₂ emissions. A landed mission carrying instruments capable of detecting the concentration of methane in atmospheric and soil-gas samples down to ten parts-per-trillion level would be required for the proposed methane mission. Determination of the concentration of other reduced gases (such as H₂, ethane, and propane) at 1-10 parts-per-trillion level would also be required. Acquisition of samples might require preconcentration (mass spectrometry/chromatography or compression) of gas samples prior to introduction of gas samples into analytical instruments. Characterization of reduced carbon compounds at 1-10 parts-per-trillion level in rock and regolith samples is strongly recommended. Acquisition of appropriate rock and soil samples would necessitate scraping, grinding, or drilling through oxidized surface materials. Determination of the concentration of reduced gases containing sulfur atoms (such as hydrogen sulfide and organosulfur compounds) at 1-10 parts-per-trillion level is strongly recommended as they are closely associated with biologic processes on Earth. Stable isotopic characterization is an integral part of inferring the origin of methane, so the analytical instruments should have the capability to determine carbon and hydrogen isotopic compositions for methane and carbon isotopic compositions for other volatile hydrocarbons. If water ice or clathrates are discovered associated with the methane discharges, then determining the stable hydrogen isotopic compositions of water and methane in these materials would be highly desirable. If hydrogen sulfide or volatile organosulfur compounds are detected, then determining the proportions of stable isotopes of sulfur would be highly desirable.

Visual inspection of the sample site or sites would be required in order to assess textural or structure evidence of an open conduit (vent, scarp face or fracture) or a diffusion pathway (pores, cavities, or open fractures in regolith, bedrock, or ice) for methane release. This type of geological information would be needed at a range of scales for submillimeter to meter on horizontal and inclined surfaces at the sampling locations. Detailed identification of minerals and elemental analysis of rocks and minerals at the sampling locations would be required to provide geological (and possibly biological) context.

13.7.3. Landing Site Considerations

Additional information would be needed prior to landing site selection with regard to the spatial and temporal distribution of methane emissions on Mars (Mumma et al., 2009). Low-orbit spectral instruments observing solar occultation could provide critical data on temperature and water content of atmospheric regions enriched in methane as a next step toward localizing sources (Smith et al., 2009a). Orbiting instruments such as CRISM and HiRISE could then be used immediately to map mineralogical, geomorphological, and structural features. Minerals enriched in carbon or sulfur could provide insightful evidence of reactions between methane and surface minerals or fluids. Landscape features such as fractures, scarp faces, or mounds could help constrain possible fluid migration pathways and release mechanisms. Decisions about stationary versus roving instrument platforms should be deferred until spatial and temporal aspects of emission are constrained.

13.7.4. *In situ* Mission Implementation

Operation of the instrument platform both day and night over at least one Mars year would be highly desirable in order to discern diurnal and seasonal variability in methane emission. If methane is detected and scientists infer a biological source, then planetary protection considerations for all types of potential Mars sample return missions would be strongly impacted. A stationary or roving instrument platform would require an articulated, long arm capable of positioning and inserting a gas-sampling probe into an open vent or fissure. The gas-sampling probe should also be designed for insertion by pushing into un lithified, porous regolith. Once the probe is in place, gas migration could occur via carrier lines

connected to a suite of high sensitivity instruments for detection and quantification of targeted molecules. Concentrations of methane, ethane, propane, butanes, di-hydrogen, and hydrogen sulfide would be the highest priority measurements for this potential mission. Stable isotopic compositions of carbon, hydrogen, and sulfur atoms in the detected gases would be a highly desirable measurement. Mineral identifications (including hydration state) and elemental compositions of geological materials at the sample site would be required for this mission. Detection and mapping of subsurface water, water ice, or gas clathrates at a methane emission site would be highly desirable to provide additional constraints on source interpretations.

13.8. Mission Concept #8: Polar Layered Deposits Traverse

13.8.1. *In situ* Scientific Objectives and their Significance

The overall objective of this mission concept would be to examine layered deposits in the polar regions in order to understand the role of recent climatic changes in their origin. The martian polar layered deposits (PLD) are widely believed to contain a record of recent global climate changes and other episodic events (Thomas et al., 1992; Levrard et al., 2007; Byrne, 2009), but this record has proven difficult to interpret from orbit (Clifford et al., 2000, 2001, 2005; Fishbaugh et al., 2008). In particular, the mechanisms by which climate changes are recorded are poorly constrained. Therefore, important questions remain regarding the PLD and the (at least recent) climate history that they record:

- What can be inferred about the secular evolution of water on Mars from the PLD record?
- Are recent global climate variations dominated by astronomical (orbit/axis) forcing?
- How do recent global climate changes on Mars compare with those on Earth?

These questions are timely and of compelling significance because terrestrial global climate changes are critically important to the evolution of life and biodiversity, yet are complex and poorly understood. The amplitude of variations in Mars' obliquity and eccentricity are much larger than Earth's, so it should be easier to understand their effects on Mars' climate. The climates of both Earth and Mars are affected by variations in solar luminosity, so recognizing such effects in the martian PLD would aid in the interpretation of the more complicated terrestrial climate record. *In situ* study of the PLD is linked to the following MEPAG Objectives:

Goal I: Objective A, Investigation 1: Establish the current distribution of water in all its forms on Mars.
+ maybe 2: Establish the current distribution of water in all its forms on Mars.

+ maybe 3: Identify and characterize phases containing C, H, O, N, P and S, including minerals, ices, and gases, and the fluxes of these elements between phases.

Goal II: Objective A, Investigation 3: Understand how volatiles and dust exchange between surface and atmospheric reservoirs, including the mass and energy balance. Determine how this exchange has affected the present distribution of surface and subsurface ice as well as the Polar Layered Deposits (PLD).

+ maybe 1: Determine the processes controlling the present distributions of water, carbon dioxide, and dust by determining the short- and long-term trends (daily, seasonal and solar cycle) in the present climate. Determine the present state of the upper atmosphere (neutral/plasma) structure and dynamics; quantify the processes that link the Mars lower and upper atmospheres.

Goal II: Objective B, Investigation 1: Determine how the stable isotopic, noble gas, and trace gas composition of the Martian atmosphere has evolved over obliquity cycles to its present state.

Goal II: Objective B, Investigation 2: Determine the chronology, including absolute ages, of compositional variability, and determine the record of recent climatic change that are expressed in the stratigraphy of the PLD.

- Goal III: Objective A, Investigation 2: Evaluate volcanic, fluvial/laucustrine, hydrothermal, and polar erosion and sedimentation processes that modified the Martian landscape over time.
- + maybe 5: Evaluate igneous processes and their evolution through time.
 - + maybe 6: Characterize surface-atmosphere interactions on Mars, as recorded by aeolian, glacial/periglacial, fluvial, chemical and mechanical erosion, cratering and other processes.
 - + maybe 8: Determine the present state, 3-dimensional distribution, and cycling of water on Mars including the cryosphere and possible deep aquifers.
- Goal IV: Objective A, Investigation 1D: Characterize potential sources of water to support *In Situ* Resource Utilization (ISRU) for eventual human missions.

13.8.2. Investigation Strategy

In order to address the above questions, the PLD must be sampled to determine the ice composition and concentration of particulates within the ice. Absolute dating of the ice would be highly desirable, but is likely to be difficult (although optical luminescence might provide useful information). Annual layers might be detectable; ice grain sizes should be measured in each resolved layer. Samples should be acquired at sufficient vertical resolution to detect layering at the cm scale or better. These observations would be required to evaluate the scale, rate of accumulation, and physical characteristics of layers in the PLD. The depth of each measurement must be recorded to support data analysis. In addition, the thickness and composition of material mantling the icy PLD would be of secondary interest. To understand current processes, atmospheric properties such as pressure, temperature, humidity, opacity and wind velocity should be monitored at least once per sol.

The required samples and observations would be acquired by rover traverse down an exposure of PLD (see Figure 13.8). Mechanical or thermal subsurface sampling approaches could be used to study the pristine icy material. A brush or backhoe could be used to remove any ice-poor mantling material (Herkenhoff et al., 2007) from the surface of the PLD before sampling the ice.

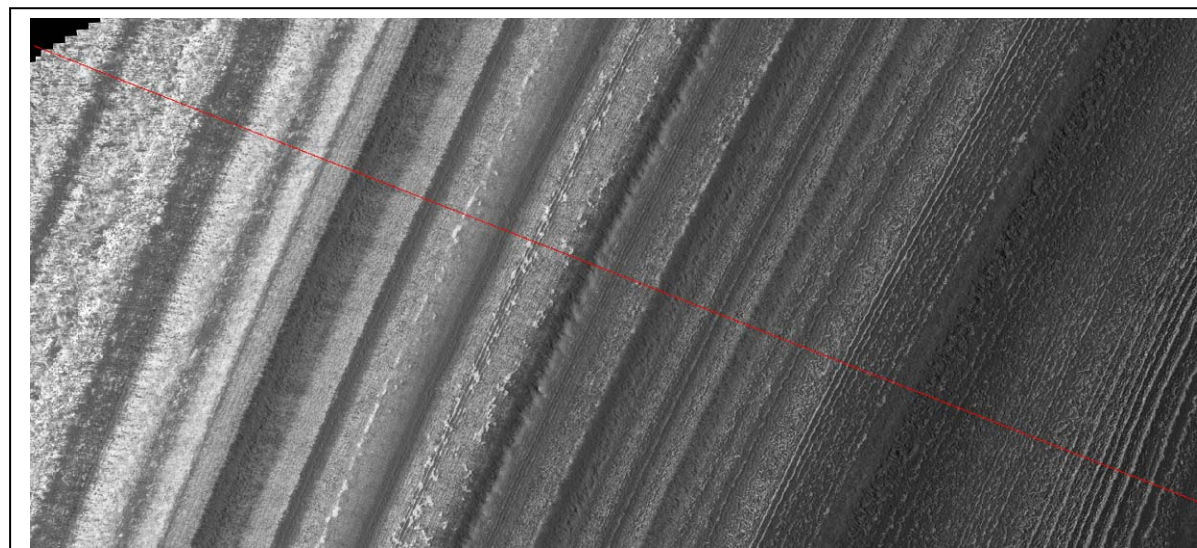


Figure 13.8. HiRISE image PSP_001738_2670 of exposure of north PLD, acquired during northern summer. Example 3.5 km proposed MAX-C rover traverse shown in red. Top of slope is at left. Credit: NASA/JPL-Caltech/University of Arizona.

13.8.3. Landing Site Considerations

The north PLD would be more accessible to the proposed mission, due to their lower elevation (-5 to -2 km relative to MOLA datum) than the south PLD (+1 to +4 km). The north PLD are exposed in many broad troughs that are separated by large expanses of flat terrain covered by the north polar residual cap. The north polar residual cap is typically very smooth (meter-scale slopes $< 3^\circ$; Herkenhoff et al., 2002) and therefore an ideal landing surface. The rover would then traverse out of the landing ellipse and at least 1 km across an adjacent PLD exposure to ensure that a significant number of observed layers are sampled. An example rover traverse is shown in Figure 13.8. HiRISE stereo data in this location have been used to determine that slopes along 2-m baselines are typically $< 10^\circ$, and 30° at most (Fishbaugh et al., 2009), which would not be hazardous to the rover.

13.8.4. *In situ* Mission Implementation

An ice corer or other means of subsurface sampling would be required to gather the ice data summarized above. Instruments, such as a color microscopic camera, conductivity probe, and chemical (isotopic) analyzer, would be deployed to the surface or into the borehole using an instrument arm. Roughly 100 boreholes would be required to adequately sample the PLD along the traverse, depending on the length of the coring drill. Note that deep drilling could be more easily accommodated on a stationary lander. Ground-penetrating radar or a seismometer with sources on the EDL back shell would be useful additions to the payload. The availability of solar power at these latitudes would require that the rover mission be completed in about 200 sols, during the summer while the PLD are exposed.

13.9. Comments by MRR-SAG Members on the 8 Mission Concepts

Table 13.1 highlights some of the typical comments provided by the MRR-SAG members during the group’s review of the 8 mission concepts.

Table 13.1. MRR-SAG comments on the 8 mission comments.

Concept Number and Title	Typical Comments
(#1) Mid-latitude Shallow Ice	“Mission concept too much like Phoenix – would be tough to sell to the general scientific community, congress, and the public. Risks low, because we have for the most part already done this.” “Focused on present life - I think searching for past life allows us to cast the net over a more promising (and larger) part of martian history.”
(#2) Noachian-Hesperian Stratigraphy	“Critical period in Mars' history; well designed mission could markedly improve understanding of geologic record.” “Good if we can be sure that the succession (and measurements) allows us to resolve the question about 'mineral epochs' and planet-wide changes in habitability.”
(#3) Radiometric Dating	“Important but very challenging. Potential downside is that selected site might offer fewer opportunities to study other science, e.g., volatile element geochemistry and astrobiology.” “Risk high due to seeming need for rapid instrument technological development.” “The value of dating the surface materials will depend on the resolution of dating.”
(#4) Early Noachian Astrobiology	“Most habitable environment of all, most active geochemical cycling of volatiles, high public interest, best chance to find evidence of life.” “Unexplored time period when life may have started.” “This is probably a subset of concept 5.”
(#5) Astrobiology – New Terrain	“Could capitalize on any one of the important recent MRO and MEX discoveries. Test additional site types that are highly viable habitability candidates. Effectively extend field studies of vast, diverse martian surface.” “High value MSR astrobiology precursor, selecting samples for life detection on Earth.”
(#6) Deep Drilling	“Proposed for ExoMars, so may be redundant.” “I’m concerned that the cost and mass of a drill would severely limit the other instruments that could be carried.” “An important measurement, but not a stand-alone mission concept. Should be included as a measurement for one of the other concepts.”
(#7) Methane Emission from Subsurface	“Could reveal exciting results about interior processes, but finding right spot is crap shoot; this mission concept should wait until better constraints on methane localities are available.” “If an actual seep could be identified then this would be a great mission. I think trying to get this done by 2018 is a bit unrealistic and our current understanding of the methane story is just too limited right now.”
(#8) Polar Layered Deposits Traverse	“The general idea is interesting, but I don't think this mission would have much to offer for sample return.” “If solar-powered, mission would be too short to achieve significant objectives.” “Very dependent on drill and relevant only for extant life.” “Expect problems roving on ice.”

14. APPENDIX C. POSSIBLE AUGMENTATION PACKAGES

This section describes some possible payload augmentation packages that could be considered as add-on(s) for the mission concepts in the previous sections of this appendix. A future MAX-C Science Definition Team should reconsider the full gamut of potential augmentation packages; these are the ones that the MRR-SAG identified as highest priority for consideration.

14.1. Atmospheric-Surface Interactions Augmentation Package

Authors of Section 14.1: Lori Fenton, Bob Haberle, Don Banfield, Rob Sullivan, Tim Michaels, and Scot Rafkin (not MRR-SAG members).

An augmentation package could be included in the proposed MAX-C mission with the scientific objective of determining the relationships governing surface/atmosphere interaction through exchange of energy (through heat and momentum), volatiles (including trace gases), and sediment transport.

Measurement of wind velocities, surface and air temperatures, relative humidity, dust emission (either through saltation impact or otherwise), air pressure, and trace gas fluxes are all necessary to determine the relationships controlling surface/atmosphere interactions. To properly characterize the exchange of momentum, heat, volatiles, and sediment between the surface and atmosphere, it would be necessary to have a dedicated suite of instruments that functions for extended periods of time and obtains precise measurements of high frequency so that subsecond, hourly, diurnal, seasonal, and interannual variations are resolved and monitored. With the current lack of martian observations, empirical relations acquired on Earth are typically applied to estimate fluxes between the martian surface and atmosphere, with unknown errors. Thus these data would be essential for understanding the current climatic state of Mars, determining potential sources of trace gases that might lead to the discovery of life, and constraining atmospheric models that are needed to ensure safe landing conditions for potential future spacecraft.

A dedicated meteorology mast, strategically located to minimize interference from the spacecraft, would be necessary to ensure robust, uncontaminated data. A network of such instruments placed at different sites on Mars would be of great value, leading to an understanding of spatial variations in surface/atmosphere interactions and allow for “weather monitoring,” like many meteorological stations on Earth. A consistently high data rate with calibrated measurements from multiple heights would be crucial to determining fluxes and resolving the turbulent structure of the near surface atmosphere. To date, no such instruments have been flown to another planet.

Even the Rover Environmental Monitoring Station (REMS) on the Mars Science Laboratory (MSL), perhaps the best meteorology instrument suite that will have been sent to Mars, has not been designed to acquire data sufficient to meet the needs listed above. For example, REMS will acquire data at a rate of 1 Hz for 5 minutes per hour, but more continuous subsecond data rates are necessary for studying the turbulent exchange of heat and momentum and its development throughout the day and night. The small eddies that can control such exchanges must be resolved with a higher sampling rate (approximately 20 Hz). In addition, the precision of the REMS anemometer is on the order of 50 cm/s, whereas a higher precision of ~1 cm/s is necessary to capture the vertical winds that determine the exchange of heat, momentum, and volatiles between the air and surface (compared to horizontal winds, these vertical winds can be relatively slow, so high sensitivity is necessary). Clearly, a new suite of instruments would be necessary to obtain the needed data.

Specifically, the measurements that would be necessary are:

- Three dimensional wind velocity (speed and direction) measurements made with accuracies of 1 cm/s and a frequency of 20 Hz, at any local time, ideally from at least three different heights along a ~2 m vertical mast.
- Air temperatures obtained with the same heights and temporal resolution as (and coinciding with) wind velocity measurements.
- Ground temperatures obtained at 1 Hz.
- Air pressure obtained with the same temporal resolution as (and coinciding with) wind velocity measurements, to determine the turbulent structure (e.g., record dust devil passage, coordinate turbulence spectrum with wind and air temperatures).
- Relative humidity obtained with the same temporal resolution and heights as (and coinciding with) wind velocity measurements.
- Mass fluxes (particle concentrations and size distributions) of migrating sediment (e.g., suspended dust and saltating sand), with measurements obtained with the same temporal resolution (and coinciding with) wind velocity measurements.
- Daytime solar and downwelling infrared fluxes, with measurements obtained at 1 Hz.
- Concentrations of trace gases (HDO, CH₄), with measurements obtained with the same temporal resolution (and coinciding with) wind velocity measurements.

Priority 1 (measurements critical for the most basic climatology):

- Simultaneous pressure, temperature, and 3-D wind velocity at a single height, located in a manner that would absolutely **minimize** the potential interference from the rest of the craft.
- Measurements taken as often as possible throughout the entire mission and any extended mission(s). This would include day **and** night. One hour sessions with a measurement cadence of 20 Hz should be included during the day.
- All instantaneous measurement data should be relayed to Earth.

Priority 2 (necessary for a meaningful understanding of surface/atmosphere interaction):

- Simultaneous temperature and 3-D wind velocity at 3 **different heights** and air pressure at a single height, with the same timing and placement criteria listed in Priority 1.
- Ground temperature measurements at 1 Hz.
- Overall system should be at least able to meet Priority 1 criteria/goals.

Priority 3 (useful for more complete understanding of surface/atmosphere interaction):

- Aerosol (dust, ice crystals, etc) concentration and size distribution; including short (~10 minutes) sessions of 20 Hz daytime measurements.
- Relative humidity (water substance) obtained at the same heights as the three 3-D anemometers, obtained with the same timing and placement criteria listed in Priority 1.
- Downwelling infrared and solar fluxes obtained at 1 Hz.
- Overall system should be at least able to meet Priority 1 and 2 criteria/goals.

Priority 4 (interesting measurements that could reveal much about the martian climate system, potentially of value to the search for life):

- Trace gas concentrations (e.g., CH₄, HDO).
- Overall system should be at least able to meet Priority 1, 2, and 3 criteria/goals.

14.2. Paleomagnetism Augmentation Package

Authors of Section 14.2: Ben Weiss and Carol Raymond (not MRR-SAG members).

Mars presently does not have a core dynamo magnetic field, but the discoveries of intense magnetic anomalies in the ancient southern cratered terrain by the Mars Global Surveyor mission (Acuna et al., 1998) and remanent magnetization in martian meteorite ALH 84001 (Kirschvink et al., 1997) provide strong evidence for a martian dynamo active during the Noachian epoch. The time of origin and decay of this global field is poorly constrained but has critical implications for planetary thermal evolution, the possibility of early plate tectonics, and the evolution of the martian atmosphere and climate (Stevenson, 2001).

Scientific questions

Paleomagnetic studies yield two pieces of information: the intensity and the direction of ancient fields. Because the original stratigraphic orientations of martian meteorites are unknown, all Mars paleomagnetic studies to date have only been able to measure the paleointensity of the martian field (Weiss et al., 2008). *In situ* paleomagnetic studies from a Mars rover would provide unprecedented geologic context and the first paleodirectional information on martian fields. The data could be used for at least four very important scientific questions:

- (1) When was the martian magnetic field present and when did it disappear? Did the death of the martian dynamo lead to atmospheric loss and climate change?
- (2) Did ancient magnetic fields definitely arise from a core dynamo?
- (3) How did the martian paleofield vary in time? Did it experience reversals and secular variation and if so what were their frequencies?
- (4) Did Mars experience plate tectonics and/or true polar wander?

Measurement strategy

Two end member configurations for a rover paleomagnetic package could address the above questions: (A) a gradiometer mounted on a boom or rover arm for mapping of outcrop fields similar to that previously on the Lunokhod 2 lunar rover (Dolginov et al., 1976) and (B) a rock magnetometer for measuring the magnetic moment of extracted samples (Figure 14.1). The relative advantages of the outcrop field sensor are that it would require little instrument development and no rover drill. The relative advantages of the rock magnetometer are that it would uniquely measure magnetic moment, offer the possibility of demagnetization, and could be used to distinguish remanent from induced magnetization. Both configurations take advantage of more than four decades of space magnetometry instrumentation development (Acuna, 2002).

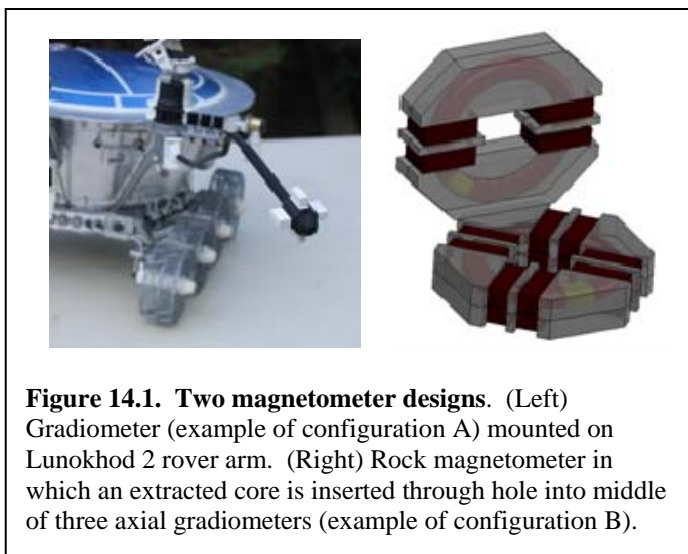


Figure 14.1. Two magnetometer designs. (Left) Gradiometer (example of configuration A) mounted on Lunokhod 2 rover arm. (Right) Rock magnetometer in which an extracted core is inserted through hole into middle of three axial gradiometers (example of configuration B).

In order to answer the above 4 questions, the following measurements would be necessary. They are listed in order of priority.

Priority 1: Determining the time when the martian dynamo was active and disappeared would likely require a traverse of rocks of Noachian and Hesperian age. Possible locations where this could be achievable in a 10-15 km rover operations area include localities Nili Fossae (Mustard et al., 2008), which contains some of the oldest bedded lava sequences on Mars, and localities where megabreccia basement is overlain by younger sediments or lavas (e.g., Holden crater (Grant et al., 2008)). *Since answering this question would require measuring magnetization intensity and not direction, it is not required that the target rocks be part of a stratigraphic sequence or have recognizable bedding indicators if there is independent geologic information constraining their relative ages.* If the disappearance of remanent magnetism is shown to predate lithologic evidence for climate change, this would be consistent with the hypothesis that the loss of the atmosphere was connected to the loss of the protective magnetic field. This question could likely be answered equally directly by both magnetometer configurations A and B.

Priority 2: Although the predominant hypothesis for martian crustal magnetism is a core dynamo, there are other (albeit highly unlikely) possibilities including impact magnetization and lightning. A core dynamo model would be confirmed by measurements from one or more Noachian outcrops containing rocks whose original orientation could be reconstructed from geologic bedding indicators as revealed in imaging data. An alternative possibility if such outcrops are not available would be to use megabreccia blocks (Grant et al., 2008; McEwen et al., 2008), many of which show clear layering which could be used to reconstruct their original orientations. Measurements of oriented samples would provide the first paleodirectional constraints on martian paleofields, which could be used to search for a number of telltale indicators of a core dynamo including coherent magnetization directions at the local geologic scale, dipolar field geometry at larger scales and geomagnetic reversals. Although magnetic reversals are typically identified using laboratory measurements (using a device similar to magnetometer configuration B), some of the first magnetostratigraphic maps were made with portable magnetometers similar to configuration A (Einarsson and Sigurgeirsson, 1955; Einarsson, 1957; Sigurgeirsson, 1957; Rutten, 1960) (see also Kristjansson and Johannesson (1999) and Coe et al. (2004) for recent applications of the technique). Therefore, although this question could be more readily answered with magnetometer configuration B, it could also be addressed with configuration A. This goal would likely require surveys of oriented samples at widely distributed points or a unique location with a stratigraphic succession that could be oriented.

Priority 3: Paleomagnetic measurements of rocks from a stratigraphic sequence would be the first continuous time records of the martian magnetic field and would permit the identification of geomagnetic reversals and secular variation of the ancient dipole field. Such magnetostratigraphic records could be used as a correlative tool for relative dating and would also provide fundamental constraints on convection in the martian core. Again this question would require rock samples with paleo-orientation indicators. It could be more readily answered with magnetometer configuration B but could also be addressed with configuration A.

Priority 4: One of the most important contributions of paleomagnetism to earth science is the evidence it has provided for plate tectonics (Runcorn, 1965) and the possibility of true polar wander (wholesale rotation of the planet's solid outer shell) (Evans, 2003; Maloof et al., 2006). Both processes have also been hypothesized to have occurred on Mars (e.g., Melosh, 1980; Connerney et al., 1999; Nimmo and Stevenson, 2000; Perron et al., 2007). Measurements of the magnetization direction in rocks could be used to test these two hypotheses by determining the past positions of terranes on Mars relative to a presumed axial dipole. Again this question would require rock samples with paleo-orientation indicators.

The angular precision needed for measuring rock magnetization to determine paleolatitude would likely require magnetometer configuration B.

Instrument Specifications

The two end-member instrument configurations have very different resource envelopes. The outcrop magnetometer (configuration A) is the simplest and would require the least dedicated rover support. It would use the rover mobility (both its traverse capability and articulated arm) to perform the surveys with a simple instrument and a careful experiment plan. In this scenario, an instrument with a sensor head of a few hundred grams on the rover arm would be connected to a small electronics box of < 500 g on the rover. A second sensor on the rover would allow the rover magnetic fields to be isolated from the signal of interest. Orientation information obtained by imaging would be exploited to orient samples for paleodirectional analysis. In configuration B, the rover arm would need to deliver drilled or float samples that have been marked with their *in situ* orientation into a measurement chamber for paleodirectional evaluation, and could be heated to perform thermal demagnetization to derive a more precise picture of the original directions. The magnetometer in configuration B would be a bit more massive due to the coil systems, but still would be < 1.5 kg, not including the drill/sample handling mechanism or oven. Data volumes for either scenario would be low for both configurations would be (on the order of 3 kb/s during measurement intervals).

15. APPENDIX D. SOME NOTES ABOUT POSSIBLE WAYS TO REDUCE THE MASS OF THE ROVER

A subteam within the MRR-SAG was formed to consider a range of strategies for reducing the mass of a potential sample caching rover as a precursor for a possible sample return, especially in light of the possibility that such a rover might be launched together with ExoMars. Although both science and engineering options exist for reducing the mass of the rover, this team focused primarily on the recommended science floor and measurement requirements for an *in situ* payload for the rover with the following guidelines:

- (1) The science floor represents a minimal set of capabilities for a viable mission that would meet the objectives outlined in the charter provided to the MRR SAG. Reduction beyond this set of capabilities would require reconsideration of mission objectives.
- (2) MAX-C should be a stand-alone mission independent of ExoMars, and
- (3) MAX-C should be a building block for potential Mars Sample Return.

The *in situ* measurements discussed below are considered to be the minimum set that would be needed to identify, collect, and cache an outstanding set of rock core samples as a prelude to potential sample return. Because potential sample return would place great emphasis on samples that could provide evidence for signs of life and habitable environments, the rover must have the capability to examine samples for the presence of such evidence *in situ*, and the minimal set of observations/instruments reflects this requirement. We recognize that there are many other important *in situ* scientific measurements that could be made at the surface (e.g. atmospheric pressure and temperature). However, these measurements were placed above the science floor because they are not critical for a potential sample return.

Rover Mast Measurement Requirements

A color stereo imager similar to that employed by the MERs was considered to be a critical component of the science floor. This would include a fixed field of view, Pancam resolution, and a color Bayer filter in order to survey the landing site and to locate scientifically compelling targets for sampling. While we also recognize the scientific value of having a removable solar filter in one of the cameras to aid with atmospheric dust opacity measurements, the need for a solar filter is primarily engineering-based and therefore this option was placed above the science floor. In order to select scientifically interesting samples for more detailed analysis, there is also a need for remote spectroscopy to identify a broad range of minerals at the landing site including igneous or authigenic (deposited in a subaqueous environment) minerals at distances ranging from the robotic arm workspace out to infinity. This remote spectroscopy measurement would require image or 2-D raster data of at least 20 mrad resolution.

Rover Arm Positioning and Measurement Requirements

The science floor for the rover arm includes the ability to produce fine scale images and measure the elemental composition, fine scale mineralogy, and organic composition of rock abraded surfaces. There is a critical need for the robotic arm to have at least 5 degrees of freedom and be able to position the instruments and coring tool on the abraded area and coregister the four arm measurements (imaging, elemental composition, mineralogy, and organic detection) as well as the coring device. In order to acquire in-focus imaging and high signal-to-noise measurements, the arm must be able to move toward and away from the rock surface in small (~1-2 mm) steps. A close-up imager with Bayer filter color could be used for fine scale imaging at a minimum 30 micron/pixel (MER-like) resolution. Bulk

elemental composition of the abraded surface should be obtained on a measurement spot size of ~1.5 to 2.5 cm diameter (similar to the MER and MSL APXS instruments). In order to measure the fine scale mineralogy of the abraded surface, the ability to identify a broad range of minerals, including key authigenic minerals (e.g. phyllosilicates, sulfates, carbonates, chlorides, and silica minerals formed in a subaqueous environment) as well as specific minerals within these groups at the 10% abundance detection level or better is required. Mineral identification images or 2-D raster mineralogy data of at least 60 micron/pixel would be needed as context for coring and x-y information. The detection of reduced carbon and trace quantities of a broad range of organic compounds is another critical measurement for selecting the best possible rock samples for a potential cache. Two dimensional images of the organic content of the abraded surface area at a resolution of at least one core diameter (~ 1 cm) or individual spot sizes that can be located to within 1 mm should be obtained. In addition, the ability to coregister the organic data with the mineralogy and texture of the abraded surface is highly desired.

Rover Platform and Sample Coring and Caching Requirements.

The MEPAG ND-SAG (2008) recommendation for the potential sample cache was to collect at least 10 gram rock samples and prepare a cache of 28 sample cores. The science floor for the proposed MAX-C cache is 20 sample cores (including at least 1 control blank core) and 3 spares. The spare positions in the cache are not for returnable sample cores, but provide the ability to swap out previously cached cores if, during operations, a more valuable core is identified for the potential sample return. A contamination control blank (e.g. MSL-like fused silica brick) should be included on the rover platform and be sufficiently large to be abraded and cored. The control blank would be essential for documenting the contamination environment (especially organic compounds) of the rover sample acquisition, coring, and encapsulation system.

Although this team focused primarily on the minimum science floor for a reduced-mass rover, there are several other non-measurement related possibilities to reduce the mass of the rover system that could be considered including attitude control, rover lifetime, mast height, wheel size, solar panel size, etc.

16. APPENDIX E. PLANETARY PROTECTION CONSIDERATIONS FOR FUTURE MISSIONS THAT CACHE SAMPLES FOR POTENTIAL RETURN TO EARTH

Author of Section 16: Karen Buxbaum (not an MRR-SAG member).

There are three main aspects of planetary protection for Mars missions. In simple terms, our exploration missions must avoid harmful contamination of Mars with Earth life; protect the Earth from potentially harmful effects caused by returned samples; and avoid false positive life detection events during the course of sample examination either *in situ* at Mars or back on Earth during biohazard assessment. COSPAR and NASA Planetary Protection Policies address these considerations, but they do not specifically address how to apply the policy in the case of a sample return precursor mission that could be caching a sample or set of samples for return by a subsequent mission (COSPAR, 2008; NASA, 1999; NASA, 2005). Nevertheless, it is possible to interpret the intent of the policies and determine the implications for a potential sample-caching rover mission.

All missions to Mars that contact the planet have to satisfy quantitative controls on biological cleanliness in order to avoid harmful contamination of Mars itself. The implementation requirements are mission-specific, depending principally on what part of the planet is targeted for exploration and the nature of the hardware involved. Key considerations are such things as whether the hardware would come in contact with water, whether there would be subsurface penetration, the use of nuclear power sources, etc. These controls are often referred to as “forward planetary protection.”

Any mission to Mars that is designed to return hardware and a sample to Earth is required to satisfy extraordinarily strict controls intended to minimize, to specified levels, the potential risk of harmful contamination of the Earth’s biosphere. The three main elements of the requirements are referred to as breaking the chain of contact with Mars, assured containment, and biohazard assessment; taken together, they are often referred to as “back planetary protection.” Although a sample return mission would have to meet such requirements, a precursor mission that only caches the sample would not have to implement the back planetary protection requirements.

Finally, if a Mars mission is designed to collect and package samples for subsequent return to Earth, there are planetary protection implications associated with the risk of sample contamination with Earth life. This is often referred to as “round trip planetary protection” and it should not be overlooked for the special case of a sample-caching mission. Planetary protection policy for a Mars sample return presumes that samples would be treated as potentially harmful until shown otherwise through a predefined protocol of tests conducted under strict biocontainment. Of course, the protocol would include tests to search for signs of extraterrestrial life in the sample. Thus, whether the mission itself would be designed to search for extant martian life or not, planetary protection considers that a sample return mission is a life detection mission for the purpose of establishing requirements on the flight system. One of the main requirements for a life detection mission is to design hardware and operational approaches to minimize the risk of detection of Earth life in the sample that could be confused with martian life.

Separate from planetary protection, there would certainly be significant challenges in organic and inorganic contamination control driven by whatever *in situ* science were ultimately to be incorporated in the mission and, more significantly, by the requirements established to assure maximum value of science to be performed for decades using the returned samples on Earth. The molecular contamination control implications of caching might be even more challenging than the planetary protection biological controls. Although the drivers for the actual requirements are different and would be established through different processes, the implementation options might be highly correlated. Design teams should include expertise and make the effort to analyze these challenges early in formulation.

17. APPENDIX F. ACRONYMS AND ABBREVIATIONS

AGU American Geophysical Union
AOES Advanced Operations and Engineering Services
APXS Alpha Particle X-ray Spectrometer
COSPAR Committee on Space Research
CRISM Compact Reconnaissance Imaging Spectrometer for Mars
CTX Context Camera
D/H Deuterium/Hydrogen
DUV Deep Ultraviolet
EDL Entry, Descent, and Landing
EGU European Geophysical Union
EPSC European Planetary Science Congress
ESA European Space Agency
ESP Extended Science Phase
EXM ExoMars
GSFC Goddard Space Flight Center
HEM-SAG Human Exploration of Mars Science Analysis Group
HiRISE High Resolution Imaging Science Experiment
iMARS International Mars Architecture for the Return of Samples
ISRU *In Situ* Resource Utilization
ITAR International Traffic in Arms Regulations
JPL Jet Propulsion Laboratory
LIBS Laser-Induced Breakdown Spectroscopy
LPSC Lunar and Planetary Science Conference
MAPG Mars Advanced Planning Group
MARSIS Mars Advanced Radar for Subsurface and Ionosphere Sounding
MART Mars Architecture Review Team
MATT Mars Architecture Tiger Team
MAV Mars Ascent Vehicle
MAVEN Mars Atmosphere and Volatile Evolution
MAX-C Mars Astrobiology Explorer-Cacher
MEPAG Mars Exploration Program Analysis Group
MER Mars Exploration Rover
MEX Mars Express
MIDP Mars Instrument Development Program
Mini-TES Mini-Thermal Emission Spectrometer
MGS Mars Global Surveyor
MMRS Mars Microbeam Raman Spectrometer
MOLA Mars Orbiter Laser Altimeter
MPF Mars Pathfinder
MPR Mars Science Prospector
MRO Mars Reconnaissance Orbiter
MRR Mid-Range Rover
MRR-SAG Mid-Range Rover Science Analysis Group
MSL Mars Science Laboratory
MSR Mars Sample Return
MSR-L Mars Sample Return Lander
MSR-O Mars Sample Return Orbiter
MSS-SAG Mars Strategic Science Assessment Group
MSSS Malin Space Science Systems
NASA National Aeronautics and Space Administration

NASA HQ National Aeronautics and Space Administration Headquarters
ND-SAG Next Decade Science Analysis Group
NRC National Research Council
ODY Odyssey
OMEGA Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité
Pancam Panoramic Camera
PHX Phoenix
PIDDP Planetary Instrument Definition and Development Program
PIXE Particle-Induced X-ray Emission
PLD Polar Layered Deposits
PSP Primary Science Phase
RAC Robotic Arm Camera
RAT Rock Abrasion Tool
REMS Rover Environmental Monitoring Station
SAG Science Analysis Group
SAM Sample Analysis at Mars
SHARAD Shallow Subsurface Radar
SNR signal-to-noise ratio
SWIR short-wave infrared
TGM Trace Gas Mission
TRL Technology Readiness Level
USGS U.S. Geological Survey
UV Ultraviolet
XGT X-ray Guide Tube
XRF X-ray Fluorescence